Heading in Children and Youth Football (Soccer) –

Exposure and the Impact on Neurocognitive and Vestibular Performance

Cumulative Dissertation

For the academic degree of

Doctor rerum medicinalium

(Dr. rer. medic.)

by

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2024

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November 04, 2024

Declaration of Authorship

I hereby declare that this dissertation is, to the best of my knowledge and belief, the result of my own research. All co-author contributions are presented for each publication. The work has not been submitted, either partly or completely, for a degree at this or another university. Content and ideas from other sources have been – to the best of my knowledge and belief – cited throughout the work.

I have read, understood, and accepted the PhD regulations (“Promotionsordnung NW”) in its version of 31st of March 2021 (AM.UNI.PB 10/21).

Paderborn, 04.11.2024 ________________________

Rebecca Reeschke

Danksagung

An allererster Stelle möchte ich mich bei meinem Doktorvater *Prof. Dr. Dr. Claus Reinsberger* bedanken. Vielen Dank für dein mir von Beginn an entgegengebrachtes Vertrauen und die Möglichkeit mich wissenschaftlich, wie auch persönlich weiterentwickeln zu können. Von dir konnte ich auf verschiedenen Ebenen unglaublich viel lernen. Besonders für deine wertschätzende Unterstützung, Betreuung und dein Verständnis während aller (nicht nur durch die Coronapandemie gekennzeichneten) Herausforderungen der letzten Jahre möchte ich dir danken!

Vielen Dank an *Prof. Dr. Werner Krutsch* für die Bereitstellung des Kopfballprotokolls und für die Übernahme des Zweitgutachtens dieser Dissertation.

Ein riesengroßes Dankeschön gilt außerdem meinen ehemaligen studentischen Hilfskräften *Romina Müller, Leonie Schmidt, Jonas Schröder, Darius Krösche, Theresa Koch, Hannes Niemann* und *Alexander Böhnhardt*, die bei Wind und Wetter auf dem Fußballplatz standen, um alle Fußballspiele und Trainingseinheiten aufzuzeichnen. Tage- und nächtelang habt ihr Fußballvideos ausgewertet und jeden einzelnen Kopfball akribisch analysiert. Ohne eure zuverlässige und unermüdliche Unterstützung in der Datenerhebung und Kopfballauswertung wäre dieses Projekt nicht möglich gewesen!

Danke an die Vereine *SC Paderborn, Delbrücker SC, Paderborn Baskets 91* und *Volleyball Regionalkader Paderborn (VoR)* sowie an alle Spieler für die Teilnahme an der Studie. Insbesondere *Thorsten Koch* und *Hubertus Austerschmidt* möchte ich hier nennen, die für einen stetigen Austausch bereitstanden und die Studiendurchführung samt aller notwendigen Planänderungen unterstützt haben. Ich bedanke mich bei dem *Bundesinstitut für Sportwissenschaft* für die finanzielle Unterstützung zur Durchführung der Studie.

Vielen Dank dem gesamten *Team des Sportmedizinischen Instituts*. Ihr habt maßgeblich dazu beigetragen, meinen Horizont über das Dissertationsthema hinaus zu erweitern, meine wissenschaftlichen Kompetenzen weiterzuentwickeln und aus allen Hochs und v.a. Tiefs bestärkt und motiviert hervorzugehen. *Christian Gölz* und *Roman Gaidai* möchte ich für die Unterstützung bei Angelegenheiten zur REDCap Datenbank danken. Besonders hervorheben möchte ich meine (teils ehemaligen) Kolleginnen, Büronachbarinnen und Freundinnen *Franziska Mund* und *Lena Dautzenberg*, die mich bereits im Studium begleitet haben und ohne die ich nicht stehen würde, wo ich heute stehe. Vielen Dank für jeden fachlichen Austausch und eure emotionale Unterstützung. Auch *Katrin Hemschemeier* bin ich sehr dankbar. Du warst nicht unerheblich in die Planung der Kopfballstudie involviert und hast mir den Einstieg in das Projekt sehr erleichtert.

Danke an *Miriam* und *Helen* aus der Endspurtgruppe Promotion für den wöchentlichen Austausch während des Schreibprozesses im letzten Jahr.

Von Herzen möchte ich meinen Eltern *Karin und Klaus* danken, die mich stets dabei unterstützt haben meinen Weg zu gehen und meinen Interessen zu folgen. Auch mein *Bruder Marcel mit seiner Familie*, meine liebe *Schwiegerfamilie* um meine Schwägerin *Bianca*, die mir vor allem in sprachlicher Hinsicht ein Vorbild ist, und meine *Freunde* haben in den letzten Jahren stets für einen willkommenen Ausgleich im Privaten gesorgt – Danke!

Ein ganz besonderer Dank geht abschließend an meinen Mann *Roman*, der mir in den letzten Jahren bedingungslos den Rücken freigehalten hat – nicht nur durch das Kochen unzähliger leckerer Abendessen – und bei dem ich immer wieder Energie tanken konnte.

In liebevoller Erinnerung an meine Tochter *Clara*, die mich daran erinnert hat, was im Leben wirklich wichtig ist.

Abstract

The objective of this dissertation is to contribute to a better assessment of heading exposure in youth football and to examine the impact of repetitive heading on neurocognitive and vestibular outcomes in youth players. In a prospective longitudinal cohort study, high-level youth football players (n = 135) of the age groups Under-11, Under-15, Under-19 (all males), and Under-17 (females) were observed over a period of two seasons with standardized video analysis of every header. In 275 matches and 673 training sessions, 22921 headers were recorded. Heading frequency differed individually and was significantly lower in Under-11 players than in older cohorts. Most headers were played without heading duels, from less than 20 m flight distance, and with the frontal part of the head, particularly in training. Neurocognitive performance, vestibulo-ocular function, and postural control of youth football players improved from pre- to post-season testing, comparable to age-matched control athletes (n = 51). No association was detected between function changes and the individual total heading frequency. In contrast, a higher number of heading duels and headers played from more than 20 m flight distance was associated with lower improvements in psychomotor speed and reaction time. It may be important to make heading recommendations (for training), considering the player's age, the individual variability of heading frequency, and the type of headers. Future investigations on the impact of heading should include observations of training over a longer period and focus on specific header characteristics, in particular.

Zusammenfassung

Ziel dieser Dissertation ist es, zu einer besseren Einschätzung der Kopfballbelastung im Jugendfußball beizutragen und die Auswirkungen des Kopfballspiels auf neurokognitive und vestibuläre Funktionen zu untersuchen. In einer prospektiven Längsschnittstudie wurden Nachwuchs-Fußballspielende (n = 135) der Altersklassen U11, U15, U19 (alle männlich) und U17 (weiblich) über zwei Saisons beobachtet und alle Kopfbälle mittels standardisierter Videoanalyse ausgewertet. In 275 Spielen und 673 Trainingseinheiten wurden 22921 Kopfbälle erfasst. Die Kopfballanzahl unterschied sich individuell und war bei U11 Spielern geringer als in älteren Kohorten. Die meisten Kopfbälle wurden ohne Duell, aus weniger als 20 m Flugdistanz und mit dem frontalen Bereich des Kopfes gespielt, insbesondere im Training. Die neurokognitive Leistung, vestibulo-okuläre Funktion und posturale Kontrolle verbesserten sich über eine Saison bei Fußballspielenden, vergleichbar mit Verbesserungen altersgleicher Kontrollathleten/-athletinnen (n = 51). Es zeigte sich kein Zusammenhang zwischen diesen Veränderungen und der individuellen Gesamt-Kopfballanzahl, wohingegen eine höhere Anzahl von Kopfballduellen und Kopfbällen aus mehr als 20 m Flugdistanz mit einer geringeren Verbesserung der psychomotorischen Geschwindigkeit und Reaktionszeit assoziiert waren. In Empfehlungen für das Kopfballspiel (im Training) könnten die Berücksichtigung des Spieleralters, der individuellen Unterschiede in der Kopfballhäufigkeit und der Kopfballart wichtig sein. Künftige Studien zu Effekten von Kopfbällen sollten Beobachtungen von Trainingseinheiten über eine längere Zeit einbeziehen und einen Fokus auf bestimmte Kopfballcharakteristika legen.

List of Publications Considered for Thesis

1) **Reeschke R,** Haase FK, Dautzenberg L, Krutsch W, Reinsberger C. Training matters: Heading incidence and characteristics in children's and youth football (soccer) players. *Scandinavian Journal of Medicine & Science in Sports* 2023; 33:1821-1830. doi:10.1111/sms.14408

2) **Reeschke R,** Dautzenberg L, Koch T, Reinsberger C. Neurocognitive performance, vestibulo-ocular function and postural control in youth male soccer and basketball players of different ages. *German Journal of Sports Medicine* 2024; 75:90-96. doi:10.5960/dzsm.2024.597

3) **Reeschke R,** Dautzenberg L, Mund FK, Koch T, Reinsberger C. Heading is no homogeneous condition: Effects of different header types on neurocognitive and vestibular performance in youth soccer players. *Medicine & Science in Sports & Exercise* (submitted)

List of Other Publications

Accepted congress abstracts[1]

Reeschke R, Dautzenberg L, Haase FK, Krutsch W, Reinsberger C. Kopfbälle im Kindes- und Jugendalter – Auswirkungen auf Neurokognition und vestibulo-okuläre Funktionen. Sports, Medicine and Health Summit, Hamburg, Germany, June 2023. In: *German Journal of Sports Medicine*; 74 (4); 2023; p. 114.

Schnitker R[2], Reinsberger C. Kopfbälle im Kindes- und Jugendalter – Auswirkungen auf vestibulo-okuläre und kognitive Funktionen. Leichte Schädel-Hirn-Traumata und Kopferschütterungen im Sport - Forschung und Transfer für die Praxis, Berlin, June 2022. In: Bundesinstitut für Sportwissenschaft (Hrsg.): *Leichte Schädel-Hirn-Traumata und Kopferschütterungen im Sport – Forschung und Transfer für die Praxis*; 2022; pp. 18-20.

Schnitker R[2]**,** Haase FK, Dautzenberg L, Reinsberger C. Incidence and characteristics of heading in youth football (soccer). World Congress on Science and Soccer, Coimbra, Portugal, June 2022. In: *WCSS 2022 Booklet*; p. 74.

Schnitker R[2]**,** Dautzenberg L, Haase FK, Reinsberger C. Vestibulo-okuläre Funktion, dynamische Sehschärfe, posturale Kontrolle und neurokognitive Leistung bei Fußballspielern im Kindes- und Jugendalter. Sports, Medicine and Health Summit, Virtual Congress, April 2021. In: *German Journal of Sports Medicine*; 72 (3); 2021; p. 92.

Haase FK, Prien A, Douw L, **Schnitker R**[2]**,** Feddermann-Demont N, Junge A, Reinsberger C. Kortikale Dicke des Gehirns bei ehemaligen Profi-Fußballspielerinnen im Vergleich zu Nicht-Kontaktsportlerinnen. Sports, Medicine and Health Summit, Virtual Congress, April 2021. In: *German Journal of Sports Medicine*; 72 (3); 2021; p. 144.

[1] The first author always is the presenting author.

[2] Maiden name.

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Figures and Tables

List of Abbreviations

ADHD	attention-deficit/hyperactivity disorder
ANOVA	Analysis of Variance
BMI	Body Mass Index
CI	confidence interval
cmTBI	complicated mild traumatic brain injury
Cnc	concussion
Cnc_{sub}	subconcussive blows
CNS VS	CNS Vital Signs
CTE	chronic traumatic encephalopathy
DVA	dynamic visual acuity
DVA loss	loss between static and dynamic visual acuity
ICC	intra-class correlation coefficient
IR	incidence rate
mTBI	mild traumatic brain injury
pCTE	probable chronic traumatic encephalopathy
PPCS	prolonged postconcussive symptoms
RHIs	repetitive head impacts
SET	Stability Evaluation Test
SRC	sports-related concussions
SCC	semicircular canals
UEFA	Union of European Football Associations
vHIT	video Head Impulse Test
VOR	vestibulo-ocular reflex

1 Introduction

Football is one of the most popular sports in Germany, with more than 7 Mio. club members in total. A large part of football players are children and adolescents (more than 2 Mio.) [1]. Participation in football is associated with advantages for health. A better neurocognitive performance was observed in (youth) football players in comparison to norm samples, particularly in executive functions [2, 3]. Additionally, the general mortality, mortality from cardiovascular disease, and from cancer were found to be reduced in former professional football players compared to controls from the general population [4, 5].

Besides these beneficial effects, possible long-term impairments of brain health in football players exposed to repetitive subconcussive head impacts due to routine heading are widely discussed by media outlets and the general public [6–8]. Large retrospective cohort studies report that Scottish and French professional football players died more frequently from neurodegenerative disease compared to controls from the general population [4, 5]. In addition, an increased risk for the development of neurodegenerative disease was described in Swedish male elite players. More precisely, the risk for Alzheimer’s disease and dementia was higher in outfield players compared to population controls and goalkeepers [9]. Given that outfield players are more likely to head the ball than goalkeepers, the debate about a potential influence of head impacts has been fueled. It needs to be considered that these findings are not transferable to amateur, youth, or female players, and no direct relationship between heading and potential long-term consequences has been investigated. Although evidence of long-term effects is lacking, regulations for heading in youth have been introduced based on the findings of increased risk of neurodegenerative diseases and concerns due to ongoing brain development in adolescence [10].

In the past few years, regulations of heading provided by single football associations gained media attention. In 2016, the U.S. Soccer Federation announced a prohibition of heading in match play and training for players under the age of 11 [11]. Furthermore, the English [12] and Scottish [13] Football Associations recently published guidelines that recommend no heading practice in Under-11 players and a graduated limitation of heading in older youth age groups. In contrast to a total ban on heading, the Union of European Football Associations (UEFA) provided some preventative advice to limit the header burden on youth players. These recommendations consider factors such as ball size and pressure, as well as neck strengthening, in addition to a reduction of heading in training, for example, by decreasing the pitch size [14]. Based on this, the German Football Association introduced age-appropriate guidelines, which additionally include the advice for a reduction of long-distance headers and a consideration of regeneration time between heading sessions [15]. However, exposure to heading in youth athletes has rarely been described so far, and there is no sufficient scientific evidence to conclude an adverse impact of heading on brain health and development in childhood and adolescence.

Potential short- to medium-term effects of heading on behavioral outcomes have been investigated in previous research, but the evidence is limited, and the consequences of heading are still unknown [16–18]. Particularly, the continuous, partly rapid brain development and consequently, potential changes, for example, in neurocognitive functions or balance over time, need to be considered in investigations on effects of heading in youth athletes [19–21].

Contributing to the discussion mentioned above on potential adverse effects of head impacts due to routine heading, this thesis focuses on heading exposure and its impact on neurocognition and vestibular functions in youth players. Therefore, a prospective longitudinal cohort study was designed first to observe and describe the frequency and characteristics of heading in youth players of different age groups and then to investigate the impact of heading exposure over one season on behavioral outcomes in those players. The findings of this study are discussed in the context of current literature, and an outlook for practical implications and further research questions is presented at the end of this thesis.

2 Current State of Research

In this chapter, background information relevant to the aim of this thesis is presented. Therefore, the spectrum of mild traumatic brain injury (mTBI) will be described with a focus on sports-related concussions. Secondly, repetitive subconcussive head impacts due to heading in football will be introduced, and current findings on the quantification of heading exposure in youth football will be summarized. As neurocognitive performance, vestibulo-ocular function, and postural control can be impaired following brain injuries, the development of these functions in adolescence will be described. Finally, a synthesis of the literature on potential effects of heading on neurocognitive performance, vestibulo-ocular function, and postural control will be presented.

2.1 Spectrum of mild Traumatic Brain Injury

The mild form of traumatic brain injuries accounts for the highest amount of all traumatic brain injuries [22], with a high number of sports-related cases, particularly in children and adolescents [23]. Injury characteristics can widely differ across the spectrum of mTBI (Figure 1). While complicated mTBIs can typically be diagnosed by imaging modalities like computed tomography or magnetic resonance imaging, no evidence exists for an in vivo biomarker in single mTBIs, concussions, and subconcussive blows, the latter resulting, for example, from unintentional contact occurring in contact sports or heading in football [24]. Chronic consequences of single and repetitive types of mTBI are not well understood, while persisting postconcussive symptoms can potentially result from all diagnostic entities (e.g., single mTBIs) [24]. Repetitive subconcussive blows have been suggested to possibly represent a significant risk factor for the development of chronic traumatic encephalopathy (CTE) [25]. CTE is a neurodegenerative disease, which has been described in collision and contact sport athletes experiencing repetitive head impacts (RHIs) and neurotrauma, but also in individuals with substance abuse, epilepsy, or other neurodegenerative disease [26]. Given that subconcussive head impacts typically do not lead to acute symptoms, short- and midterm consequences are largely unknown, and potential neurophysiological and -psychological sequels can hardly be described.

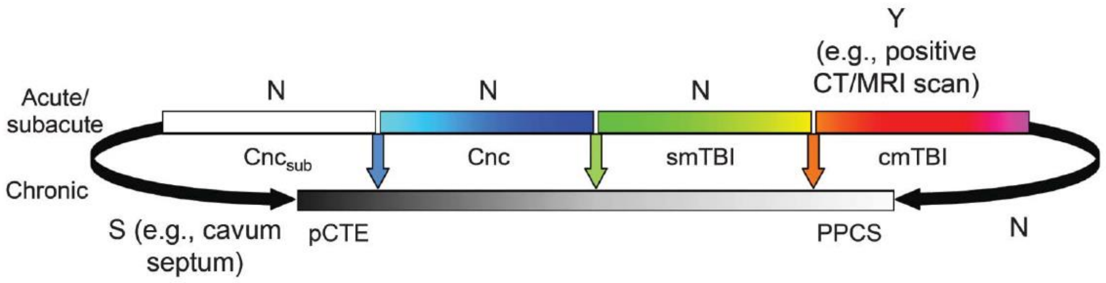

Figure 1 Spectrum of mild traumatic brain injuries (mTBIs). Abbreviations: cmTBI, complicated mTBI; Cnc, concussion; Cnc$_{sub}$, subconcussive blows; N, none; pCTE, probable chronic traumatic encephalopathy; PPCS, prolonged postconcussive symptoms; S, some; smTBI, single mTBI; Y, yes (from Mayer et al., 2017 [24]. Copyright 2017 by the American Academy of Neurology).

Concussions often occur in collision and contact sports [27]. In football, those sports-related concussions (SRC) mainly result from contact with another player, primarily in aerial duels, for example, when heading the ball [28, 29]. However, the head-to-ball contact itself typically does not result in SRC. Forces transmitted to the brain in SRC lead to “[…] a neurotransmitter and metabolic cascade, with possible axonal injury, blood flow change and inflammation affecting the brain” [30].

Given that SRC are heterogeneous injuries regarding pathophysiology [31], highly variable symptoms can occur immediately, or evolve over minutes, hours, or days [30]. Particularly, neurocognitive impairments have been found to be common in adolescents and adults after SRC, including deficits in memory, attention, processing speed, executive functions, or slowed reaction time [32, 33]. These effects have been linked to damage in white matter and neural networks, as well as neurotransmitter and synaptic alterations after concussion [34]. Also, deficits in the vestibulo-ocular reflex (VOR) and postural control are often described in concussion patients. Vestibular impairments occur in up to 80% of all SRC, ocular symptoms are present in approximately 45% of injuries [33, 35–37]. The peripheral and central vestibular systems are vulnerable to forces transmitted to the head [37], given their distributed locations and complex processes to ensure VOR function and postural control (see Chapter 2.3). Balance deficits after SRC may also occur from decreased reaction times [38], as a correlation between vestibular deficits and worsened neurocognitive function was found in children and adolescents [37].

2.2 Repetitive Subconcussive Head Impacts and Heading in Youth Football

Concussions, as well as RHIs – also designated as repetitive subconcussive blows to the head – are common in youth contact sport athletes. RHIs typically do not result in acute symptoms or concussions, whereas cumulative effects on brain microstructure have recently been indicated [39, 40]. Football, the most popular sport in German children and adolescents [1], is unique in intentionally using the head to play and control the ball. Heading the ball is an integral part of the game and therefore, players are exposed to a large number of RHIs due to headers in their careers. However, there is no standardized definition of a header so far [41].

Heading technique can be used to pass, shoot, or clear a ball from a standing, jumping, or diving position in a variety of match situations [42]. The skill of heading is motor complex [42]. In the preparation stage, the flight of the ball needs to be tracked and predicted to then make a coordinated sequence of body actions and movements for ball interception [43]. The contact between the ball and a player's head ideally should be on the forehead at or near the hairline [42]. Heading is an active skill where the trunk is hyperextended, the chin pulled to the chest, and the arms are mostly in an extended position before the hips should be flexed, arms pulled back, and neck muscles contracted when finally contact is made between the head and ball [42]. Due to its complexity, heading and precise timing need to be trained, whereby youth players may struggle with performing a proper heading technique.

2.2.1 Quantifying Exposure

A detailed understanding of the actual magnitude of heading in youth football is key to assessing potential risk from repetitive heading concerning neurological sequels, such as brain changes or diseases. For the quantification of heading exposure, not only heading frequency but also heading characteristics are of interest. There are different methods of assessing exposure to heading and RHIs:

Self-report is a feasible method to retrospectively account for heading exposure in larger populations. It allows for easy administration, is inexpensive, and requires few personnel resources. However, the method of self-reporting by questionnaires has been found to be influenced by age and sex. Youth players systematically overestimated the actual number of headers, additionally to random recall errors [44, 45]. Sex differences have been observed in prior studies, with female players overestimating exposure [46]. While players can be grouped or ranked in relation to each other regarding heading exposure, absolute numbers of headers per player are quantified imprecisely and inaccurately in adults and adolescents [44, 46]. Hence, there is a risk of recall bias and measurement errors, particularly for training-related exposure [44].

Wearable sensors represent the only method for quantifying both the frequency and magnitude of head impacts, such as linear or rotational accelerations [47]. Methods accounting for biomechanical parameters include instrumented helmets, headbands, mouthguards, skin patches, and in-ear sensors [48]. Besides a laboratory validation of devices to ensure reliability and accuracy of data [49], an on-field validation by data filtering and verification of head impact events is needed [50]. Therefore, video verification of recorded accelerative events and advanced post-processing techniques are necessary, making the use of sensors complex and time-consuming [50]. Furthermore, potential user-related challenges (e.g., device coupled tightly to the head, time-synchronization with other data sources like video) need to be considered [50, 51].

Direct observation can primarily be used to account for the number of head impacts. Registering headers in matches by trained observers was found to be a reliable method compared to video analysis [46, 52], whereas observations in training sessions and by athletic trainers or parents have not been validated so far [53]. No impact forces can be captured in observational approaches, whereas the characteristics of headers can be categorized based on subjective interpretation, such as ‘short vs. long distance’ headers [52]. Particularly in training sessions with more than one ball used at the same time, several observers are required to quantify and classify headers [46]. As the physical presence and attention of observers are critical to the feasibility of direct observations, this approach is challenging to use in prospective studies with longer periods of observation.

Video analysis can be considered a gold standard for objectively quantifying heading exposure [54], as it is an established method to assess the frequency and characteristics of head impacts [29, 55, 56]. Structured video analysis is highly resource-demanding and requires a high amount of logistical effort, particularly when used across various teams or sessions. Research personnel is required not only for the set-up of equipment and video recordings but also for the analysis of recordings. However, a repeated assessment of recorded events is possible, allowing for valid and reliable results, even in large-scale cross-sectional studies or longitudinal observations over a longer period of time [54]. The use of a standardized analysis protocol by trained reviewers is important for characterizing head impacts consistently (see, e.g., [57]).

2.2.2 Heading Frequency

Different methodological approaches for recording heading numbers have been used in previous studies. However, research results based on self-report questionnaires [58–60] or wearable devices [61–63] are unfavorable for comparisons, as they partly differed from those using observational approaches.
One of the first studies reporting heading data was published in 2002 [64]. In recent years, the interest in this area has increased, and most of all studies that describe heading exposure were published after 2020 [41]. A wide variation of objectively observed individual heading numbers performed in matches has been described amongst studies of youth athletes, ranging between less than 1 to 7 headers per player per match, on average [18, 65]. The frequency of heading the ball was found to be higher in adult than in adolescent players [66] and to depend on age and sex in youth athletes [18, 65]. Previous studies showed that heading numbers increased with age, and males were found to head the ball more often compared to females [52, 54]. In addition, heading numbers differ between (European) countries [54]. Another factor that is discussed to influence the number of purposeful headers is the playing position. Most headers were played by defenders in male youth players, whereas midfielders completed headers most frequently in female adolescents in a cross-sectional observational study [66, 67]. In contrast, no position-based differences were found in another study [63].

Instead of reporting total heading numbers over the observation period, individual numbers per player per match/training session or per hours can make study results more comparable. One approach is to use the incidence rate (IR), which is the number of incidents, such as headers per 1000 player hours [54, 68]. However, only a small number of previous studies employed such a comparable metric [41], and in the majority of studies, matches have been analyzed. Beaudouin et al. [54] analyzed heading exposure in a cross-sectional study via video observation and found lower match heading incidences in Under-10 compared to Under-12 and Under-16 males. An IR of 1677 per 1000 match hours was reported for Under-10 players, 2078 for Under-12, and 2665 for Under-16 males [54]. Under-20 males headed the ball with an IR of 1761 per 1000 match

hours in another study [69]. Individual heading exposure does not only vary between age groups but considerably within teams. It has been described that a high number of players sparsely headed the ball in matches, while heading was observed more frequently in a minority of players [52]. The heading incidence was up to 45% lower in youth females compared to males [52, 54].
Although training sessions account for the majority of overall football exposure [44, 70], systematic observation of heading during training has rarely been appropriately conducted due to logistical requirements, and heading frequency in training is less well described [18]. Considerably higher numbers in training sessions compared to matches have been observed in a large-scale cross-sectional study [54]. Particularly, Under-10 and Under-12 players showed high heading IRs of up to 5007 per 1000 playing hours on average compared to Under-16 males (IR: 2511) and females (IR: 2341) [54].

However, there is variability and limited data on the actual frequency of heading during matches and training sessions in youth players of different ages, as most of all observational studies have used a cross-sectional design so far. It can be concluded that a longitudinal observation of various matches and training cycles over an extended period of time is needed for a realistic evaluation of individual exposure.

2.2.3 Heading Characteristics

Headers can be characterized in various ways. Besides descriptors such as delivery type or the flight distance of the ball prior to the header, biomechanical magnitudes can be assessed. Head-to-ball contact forces are assumed to be an important indicator of the risk of head injuries [71, 72]. Reported head acceleration values for heading the ball (e.g., in g) were found to be below thresholds for brain injuries [73] and varied widely, depending on the methodology [43]. No established biomechanical thresholds exist for the characterization of head impacts in sports, such as headers.

The type of header [74], game scenario [63], and heading technique [71] were found to influence accelerative forces to the head. Headers played from a longer distance [70], with head-to-head contact, or while jumping [75], for example, in heading duels, lead to higher velocities and higher head impact forces. Head impact magnitudes were found to be largest when the ball originated from shots and corner kicks in youth players [63]. Headers purposefully played with the frontal part of the head, indicating a proper heading technique, are associated with lower peak rotational velocities than impacts, for example, to the top of the head, which are potentially unwanted or indicate an improper technique [63]. Overall, player characteristics such as age and sex can also affect the head impact magnitude [76, 77]. This is because factors influencing forces to the head, such as the type of headers (e.g., flight distance of the ball) [52, 54], the heading technique [63], the head and neck mass [78], or the ball size and mass [79, 80] can differ between age groups and partly between sexes.

Heading characteristics are mostly presented relative to the overall exposure. A previous large-scale cross-sectional study in Under-10 to Under-16 football players showed that match and training headers were typically played without heading duels (80% to 96%), with the frontal part of the head (71% to 87%), after short-distance shots of less than 5 m (42% to 80%) in free game play (65% to 83%) [54]. However, heading characteristics in youth players have been described only in a few studies, and there is a lack of standardized reporting criteria so far [41].

Currently, longitudinal observations of heading exposure are rare despite being much needed for a realistic assessment of the heading burden. Less is known about the frequency and characteristics of heading in training over a longer period of time, for example, over one season, and various training cycles need to be observed for a realistic evaluation. Besides heading frequency, characteristics of headers in youth players of different ages, such as the type of header, head impact location, and distance of the ball before heading are important to be considered as a potential indicator for head impact magnitudes. These factors can be assessed most valid using systematic video analysis, which is therefore not only a favored method for quantification but also for characterization of headers.

2.3 Neurocognitive and Vestibular Functions in Sports and Adolescence

Given that multiple domains – including neurocognition, vestibulo-ocular function, and postural control – can be affected following SRC (see Chapter 2.1), those diverse domains may potentially be impaired in youth athletes after exposure to RHIs caused by heading a ball. Sports and age are potential influencing factors for neurocognitive and vestibular functions and, therefore, may be essential to consider in (longitudinal) investigations of those domains in youth football players.

Neurocognitive Function

Cognitive functions allow people in everyday life as well as athletes during sports participation to extract, process, discard, and use information from the (sporting) environment. Particularly, executive functions can be important for sports performance, for instance, for tactical performance needed in football matches [81]. Domains like processing speed, cognitive flexibility, and psychomotor speed have been found to be better in athletes compared to a norm sample [2], and even a relationship between performance level and cognitive functions is assumed [82]. Neurocognition is referred to as cognitive performance resulting from neuronal processes realized in the brain and nervous system [83]. Neurocognitive domains, such as complex attention, executive function, learning and memory, perceptual-motor, language, and social cognition [84], are based on within-brain signal transmission between neurons. These neuronal connections form pathways and brain networks that facilitate complex interactions between brain regions at a functional level.

Neurocognitive functioning changes during adolescence [3]. Substantial improvements in performance are described with increasing age, while the magnitude of changes differs between neurocognitive domains [21, 86]. Among other developmental processes, brain structures and connectivity continue to change in late childhood and adolescence, with a selective reduction of synapsis due to non-use and myelination of axons [83]. Regions of the brain increasingly specialize, and the brain becomes more efficient by increased connectivity between brain regions and integrative processes [87]. As a result, these alterations allow for a higher processing speed, play an important role in memory and learning development [88], and consequently contribute to enhanced behavioral outcomes in neurocognitive performance with increasing age [20, 21]. Especially executive functions develop through childhood and adolescence [89], parallel to the structural development of prefrontal cortical regions [90] and white matter tracts, allowing for connections between the prefrontal cortex and other brain parts [91].

[3] Adolescence is defined by the World Health Organization as the phase of life between childhood and adulthood, including people aged between 10 and 19 years [85].

Vestibular Functions

The vestibular system is a complex structure that detects and controls the position and movement of the head in space. Coordination of head acceleration with associated compensation in eye movement and with posture are the main functions. Therefore, the central vestibular system in the brain responds to input from the peripheral vestibular apparatus in each inner ear. This includes otolith organs, perceiving linear head accelerations and gravitational forces, and three semicircular canals (SCC) on every side of the head, which detect angular acceleration and rotation of the head by sensory hair cells [92]. The vestibular system contributes to two primary functional elements: The vestibulo-ocular component, which integrates head movement and compensatory eye movement, and the vestibulospinal component, which helps to control posture and balance. Both the VOR and the ability to maintain postural control are essential to performing activities in daily life and participation in sports.

Vestibulo-Ocular Reflex

The VOR is a vital function of the central vestibular system and coordinates eye movement during head rotation for stabilization of gaze and retinal images [92]. When the head is turned in one direction, the eyes immediately move to the opposite side to fix a visual target. The ability to ensure a stable gaze during head movement is essential to minimize blurred vision, particularly during sports participation, where the head and body are constantly moving. This reflex is based on a complex connection between the SCC (lateral, anterior, and posterior), the vestibular nucleus, and the nuclei of cranial nerves [92]. Central pathways of the VOR are displayed in Figure 2, visualizing a VOR-caused eye movement to the right in response to a head turn to the left. The influence of sports on the VOR is not yet clear. No difference in VOR between gymnasts and a (non-gymnast) control group was found [93], whereas minor sports-specific differences were observed in team sports [94].

Neural network connections between vestibular afferents, central vestibular neurons, oculomotor neurons, and eye muscles are found to be functioning to some extent at birth. With visual input, a calibration of the VOR follows [95]. Maturation of the vestibulo-ocular pathways with age is supposed in different studies [96, 97]. Charpiot et al. [96] suggested that VOR development continues during childhood. In contrast, no influence of age in VOR assessment was found in children and adolescents [98, 99] and in youths compared to adults [100]. Hence, the development of vestibulo-ocular functions in adolescents has not been clearly described so far.

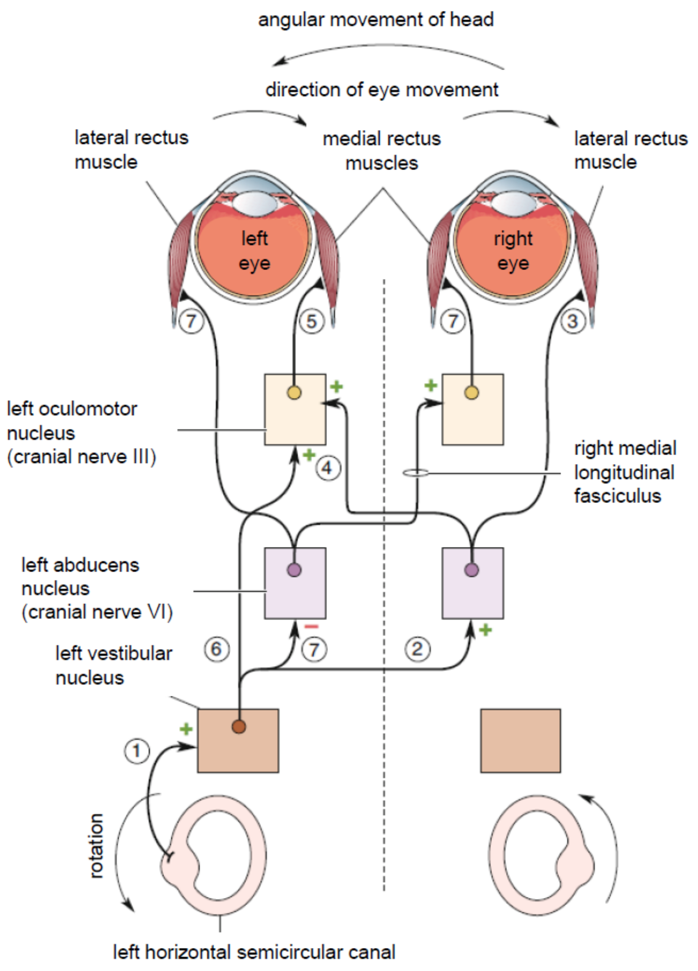

Figure 2 Vestibular pathways of the vestibulo-ocular reflex. When the head is turned to the left, the eyes show a compensatory movement to the right side, with excitatory (green plus) and inhibitory connections (red minus) (adapted from Bear et al., 2018 [92]. Copyright 2018 Springer-Verlag GmbH Deutschland).

Postural Control

Achieving and restoring a stable state of balance during any static posture or dynamic activity is referred to as postural control [101]. It is essential to control (technical) movements and maximize sports performance, as well as for injury reduction [102]. It is considered a complex interaction of multiple systems and processes, where sensory information from the visual, proprioceptive, and vestibular systems are gathered and reweighted by the central nervous system [103, 104]. The initial postural reaction is primarily generated by the vestibulospinal tract and reflexes to control the position of the

head in space (cervical reflexes) and upright posture and equilibrium [92]. Besides these reflexes, postural control reactions can be modified by cortical motion control [92]. A mental body image is generated by somatosensory, proprioceptive, and visual information, which is transmitted to the posterior parietal cortex. Based on this information, complex function loops between cortex, basal ganglia, thalamus, and cerebellum allow for movement initiation, control, and coordination [92].
The human function of balance depends on strategies used for a particular task and context. Six subcomponents have been proposed to be important for postural control [104, 105]: biomechanical constraints (degrees of freedom, strength, or limits of stability), movement strategies (reactive, anticipatory, voluntary), sensory strategies (integration, reweighting), orientation in space (perception of gravity, verticality), control of dynamics (gait, proactive), and cognitive processing (attention, learning). Additionally, experience and practice, as well as perception of the goal and context, may influence postural control performance [104, 106]. Sports practitioners have superior performance compared to controls, and high-level athletes perform better than low-level athletes [107].

The development of postural control across life appears as a U-shaped function, with the best performance in young adults [103]. An improvement in balance performance continues up to late adolescence or early adulthood [20]. As several vestibular pathways are required for postural stabilization, a coordinated development of these pathways, in combination with parts of the central nervous system, motor system, and muscles, is needed [95]. During childhood, biomechanical constraints develop and mature, as do the processes and strategies that underlie postural control [108]. An improvement in sensory integration [108], the task-specific use of different strategies [109], and progressive brain maturation [110] contribute to balance improvement in youth age. Particularly, changes in sensory weighting strategies are affected by age as the sensory systems appear to develop at different rates [108]. The somatosensory function was found to be matured by age five, whereas visual and vestibular functions continue to mature till the age of eleven to twelve and 15 to 17 years, respectively, justifying primarily visuo-vestibular dependence in children [108]. Furthermore, an increase in muscle strength and cognitive performance, such as attention (e.g., enduring focus on a given task), may account for improved postural control in adolescents compared to children [20].

2.4 Effects of Heading on Neurocognitive and Vestibular Functions in Youth

As the brain matures with ongoing myelination in adolescence and unmyelinated fibers have been found to be more vulnerable to injury than myelinated axons [111], it was found possible that the brain microstructure may be more vulnerable to accelerative forces to the head in childhood compared to adulthood [112]. Additionally, neuromuscular control of the musculoskeletal system develops during maturation [113]. Higher neck strength can result in reduced acceleration of the head during heading [114, 115] and reduce the risk of SRC [116]. Therefore, lower neck muscle strength in young athletes may be a risk factor for sports-related head injuries.

Given that multiple clinical symptoms and signs, including cognitive and vestibular impairments, may be experienced by athletes after suffering a SRC, investigations of neurocognitive, vestibulo-ocular, and postural control parameters can help to understand potential effects of heading on brain health in youth athletes.

2.4.1 Potential Effects on Neurocognitive Functions

Studies assessing neurocognitive functions in youth and adult football players have already been published more than 20 years ago [117, 118]. These studies report, for instance, that players with a high estimated heading frequency exhibited lower attention, concentration, and cognitive flexibility scores [117]. However, these studies had a cross-sectional design and retrospectively estimated heading exposure via self-report. In contrast, a systematic review and meta-analysis did not reveal conclusive evidence for a clear link between heading and impaired neurocognitive functions [17]. The majority of studies in which the frequency of heading and neurocognitive performance has been objectively quantified have been conducted with youth cohorts so far [18]. While cognitive function was not found to be negatively affected by heading in most studies, single studies reported effects on reaction time and memory [18].

Various cross-sectional [119, 120] and prospective cohort studies [61, 64, 121, 122] found no association between heading exposure and adverse neurocognitive outcomes in youth male and female football players of different ages. An acute bout of 15 headers did not result in any significant alterations in memory, visual motor function, or reaction time in a youth female cohort [121]. In line with this result, potential exercise-related improvements in cognitive function immediately after training were not associated with heading exposure during training [123]. Similarly, after a weekend football tournament, no relationship between exposure to head impacts and neurocognitive parameters was found in approximately 12-year-old players [61]. In contrast, a more recent study did show significant differences in test scores between groups with varying degrees of heading exposure, including more than 200 soccer players aged 13 to 19 [124]. After a prospective analysis of headers captured in matches over a time span of four years, players who less frequently headed the ball showed larger improvements in reaction time than players with a moderate or high heading exposure in matches. However, in this study, only 23 players were assigned to the high-heading exposure group, practice headers were not considered, and the reliability of the real-time heading recording was not checked. Another study described that football players aged 15 to 17 did not significantly improve in reaction time over the course of various training sessions, whereas control subjects did [123]. A subsequent analysis showed no effect of the total heading number on improvement in cognitive performance. Interestingly, a higher number of long-distance headers was associated with slower improvements in reaction time [123]. In the same cohort, long-distance headers were found to lead to bigger neurocognitive response time changes, which last longer compared to effects of short-distance headers [125].

The temporal progression of possible development of a heading-related influence is poorly understood. Improvements in reaction time observed immediately following the training were not affected by the self-reported number of headers in a previous study [126]. However, reaction time slowed 24 hours post heading, which was associated with an increase in heading frequency. In contrast, a reduced memory function immediately following 20 consecutive headers normalized within 24 hours and seemed to be reversible in adult amateur players [127]. Hence, the time for testing in relation to heading might be an essential factor. However, the time point when exposure to repetitive heading might lead to potential cumulative effects and possible impairments in cognitive functions is unclear.

2.4.2 Potential Effects on Vestibulo-Ocular Function and Postural Control

The impact of exposure to heading on vestibulo-ocular functions has rarely been examined so far. A cross-sectional study on a large cohort of youth and adult athletes showed that VOR values in football players were significantly higher and, therefore, better compared to those of healthy control subjects [94]. This finding may indicate that there is no negative influence of participation in football and the related exposure to heading. However, the relationship between heading and vestibulo-ocular function has not been investigated, and general beneficial effects of sports and exercise need to be considered in the interpretation of findings. A recent study investigated effects of a heading intervention on visuo-vestibular parameters in 13- to 18-year-old football players [128]. No change was found in assessment scores, such as VOR, immediately and 24 hours following 10 consecutive headers. Given that no difference was observed between the heading and control group at any time, it has been proposed that there is no effect of an acute bout of heading. Additional research is limited in its ability to provide an understanding of the impact of heading. It is possible that a lower dynamic visual acuity (DVA) observed in professional forwards compared to other positions [129] is caused by a higher heading frequency in this position [130]. However, a direct link between heading and performance cannot be concluded as headers have not been systematically recorded. A prospective cohort study of male 9- to 11-year-old tackle football players reported no influence of objectively measured impacts over three seasons on the Vestibular-Ocular Motor Screening [131]. Moreover, even impacts with a higher intensity (forces of more than 43 g) did not predict outcomes in this study. However, studies prospectively assessing the effects of a realistic heading exposure on vestibulo-ocular parameters over several sessions or months are missing.

A systematic review focusing on the association between RHIs and changes in postural control in youth and adult athletes showed heterogeneous results [132]. An additional review in youth football confirmed that findings on effects of heading are not conclusive [65]. In single heading intervention studies, differences in postural control between football and control athletes were found, indicating that there may be balance deficits immediately following heading [65, 132]. In one investigation, a large cohort of 13- to 20-year-old football players has been divided into either a heading or a control group [133]. In comparison to control athletes, a significant increase in sway velocity was observed among the athletes who had performed twelve headers. However, no group differences occurred for most balance measures in this study. This is in line with a recent investigation of youth football players of different ages, which displays that postural sway did not change immediately or one day post heading in players who consecutively headed ten balls [128]. In contrast, alterations in postural control following acute bouts of heading were observed in college players [134, 135]. However, these changes disappeared 48 hours post heading [134]. Studies examining effects of playing football and heading over a longer period of one season presented no significant results. In detail, there was no association between various postural control parameters and exposure to head impacts (captured via helmet-based sensors) after one season in football players aged 9 to 11 [136]. However, no video verification of headers has been conducted. Similarly, in another cohort of youth and young adult players, heading frequency, directly observed in matches, did not correlate with balance performance after twelve to fourteen weeks of season, whereas training sessions have not been observed [122]. A study on young women football players observed no associations between exposure to RHIs (quantified by accelerometers embedded in headbands) and balance performance, whereas a higher number of impacts with high linear accelerations of more than 98 g was related to worsened tandem gait performance [137]. However, the impact of different heading types (e.g., flight distance) on postural control has not been investigated in youth players so far.

In conclusion, previous studies indicate that heading exposure does not seem to have an overall negative influence on neurocognitive and vestibular functions in youth football players. However, findings are inconclusive and shortcomings in the methodology of existing studies have been identified, which limit the validity of results [16, 18]. Studies investigating the impact of heading in a prospective design with an objective assessment of heading exposure across various months or years are rare, particularly for the investigation of vestibular functions. Objective heading assessment by means such as standardized video analysis is essential for evaluating realistic heading exposure. In the interpretation of previous findings, it needs to be considered that many studies on youth athletes are based on headers solely observed in matches [61, 122, 124] or single sessions [120, 121]. Therefore, the impact of the overall exposure to heading (including matches and training sessions) has not been investigated. Additionally, characteristics of headers may potentially influence outcomes [132] and may serve as an indicator of the magnitude of head impacts. However, a differentiation was rarely made between different types of headers. Consequently, both the frequency and characteristics of headers should be examined. Small sample sizes [61, 123, 126, 128] and a missing inclusion of appropriate control athletes [61, 124, 126, 136] limit the generalizability of previous results. In addition, the use of a variety of neurocognitive and vestibular tests needs to be considered in the comparison of findings [18]. The test battery conducted might potentially have an impact on performance measures. Thus, there is a need for the use of comparable, objective testing methods. These aspects should be focused on in order to gain a better understanding of potential associations between heading and functional performance.

2.4.3 Objective Assessment of Neurocognitive and Vestibular Functions

Measurement methods related to concussions (e.g., computerized neurocognitive measures) have already been applied in research on heading in football. For a multimodal assessment of different domains, an interdisciplinary approach is mandatory, using different tests [138]. Particularly, computerized tools can assist in an objective performance evaluation and the investigation of potential effects of heading.

Neurocognitive testing is an important component in the diagnosis and management of SRC. In testing, a minimum of the following should be assessed: memory, attention, and executive function domains, such as reaction time [30, 138]. Computerized test batteries, such as the CNS Vital Signs (CNS VS), are regarded to be useful in the assessment of neurocognitive performance, as the administration and interpretation of results are simple and objective [30]. The CNS VS is a self-administered neurocognitive assessment tool with a core battery consisting of seven widely used neuropsychological tests [139]. These include tests of verbal and visual memory, finger tapping, symbol digit coding, the Stroop Test, a test of shifting attention, and the continuous performance test. The test battery was found to be reliable, valid, and sensitive to different causes of cognitive impairment in children and adults, including traumatic brain injuries [139]. Once the conduction of the CNS VS battery has been completed, an automated validity indicator is generated for each subtest, indicating the potential for invalid test results due to misunderstanding or low effort [139]. Subjects' scores are presented for eleven domains, such as memory (verbal and visual), psychomotor speed, reaction time, complex attention, cognitive flexibility, and processing speed. Data are presented as raw scores and standard scores based on a norm sample [140]. Higher subject raw scores represent better neurocognitive performance for all domains, excluding reaction time and complex attention (inversely).

In addition, an assessment of vestibular functions may be informative in the investigation of potential cumulative effects of subconcussive impacts, as vestibular deficits were found in adolescents with SRC [37]. An objective quantification of the VOR can be achieved by the video Head Impulse Test (vHIT), which has been used in adolescents with mTBI [141]. The vHIT is capable of detecting peripheral vestibular dysfunctions [142] and has been validated against the gold standard scleral search coil technique [143]. The right eye is recorded with monocular goggles to capture the response of eye movement to rapid, passive, and unpredictable turns of the participant's head to measure the ratio between eye and head movement velocity, called VOR-gain. A gain value of 1 indicates that the movement velocity of the eyes is precisely the same as the velocity of the head turn in the opposite direction. When the eyes rotate at a velocity below that of the head movement, a value less than 1 is estimated. Test-retest and interrater reliability for VOR-gain were found to be high, also in the pediatric population [144].

Testing of the DVA can assess the ability to maintain gaze and see clearly while actively rotating the head, based on the VOR. The influence of potential VOR impairments in combination with the participant's adaptive response to impairments is quantified. Computerized DVA assessment has been implemented in mTBI research [141] and was found to be a sensitive and suitable tool for detecting peripheral vestibular dysfunction [145, 146]. Following an assessment of the static visual acuity, the DVA is determined by the identification of the optotype E, visualized on display, during active head turns. The loss between static and dynamic visual acuity is described by the DVA loss (in logMAR), with lower scores close to zero indicating better values and performance in the DVA. Inter-rater and test-retest reliability of DVA values were found to be fair to excellent [147].

To assess static stability and sensory integration, instrumented measures are commonly used in the clinic and research of SRC, besides the conduction of examiner-related, more clinical assessments (e.g., Balance Error Scoring System) [148]. The postural sway can be recorded using the center of pressure via a static force plate for an objective measure of postural control, for example, by the Stability Evaluation Test (SET) [103]. Balance assessment by the use of force plates was described to be sensitive to changes in postural sway after concussion [149]. To measure the participant's ability to effectively use and process vestibular and proprioceptive information for the control of upright posture during the SET, the double-leg, single-leg, and tandem stance are performed on a firm and on a foam surface, with the participant's eyes closed (20 seconds per stance). In general, lower sway velocity scores (in degrees per second) indicate a better performance in postural control. The recording of the participant's sway velocity by the SET has revealed good to excellent test-retest reliability [150].

3 Aims and Research Questions

The overall research aim of this thesis is to contribute to a better (risk) assessment of heading in youth football. The objective is to explore heading exposure and consequences of repetitive heading in youth football on behavioral (neurocognitive and vestibular) outcomes. There is little knowledge about heading frequency and characteristics of headers played in youth age, particularly in training, constituting the highest amount of overall football exposure. Additionally, there is no consensus on how heading influences neuropsychological and -physiological functions in youth athletes, such as neurocognition, vestibulo-ocular function, and postural control.

In response to these missing insights, the first aim of this thesis is to describe the frequency and characteristics of headers in male and female high-level youth football players of different age groups. To reach this aim, a standardized video analysis was carried out over two seasons of match play and training. The second aim is to investigate the impact that participation in football and individual heading exposure have on neurocognitive functions, the VOR, DVA, and postural control in those players. Therefore, differences in performance between adolescent football players and athletes of other ball sports are evaluated, and the relationship between individual heading exposure and function changes after one season is investigated.

Consequently, the following research questions are addressed:

1) How frequently do high-level youth football players of different age groups head the ball in match play and training, and are there differences in heading frequency among age groups? What are the characteristics of headers in youth football? (See research paper 1)
2) Are there differences between active youth football players and athletes of other ball sports in neurocognitive performance and vestibular functions such as VOR, DVA, and postural control? How do functions differ between youth age groups? (See research paper 2)
3) Do neurocognitive performance, the VOR, DVA, and postural control change from pre- to post-season in youth football players, and are alterations in functions associated with the individual heading exposure (frequency and characteristics) of players? (See research paper 3)

4 Study Design and Methods

To address the research aims and questions of this thesis, a prospective longitudinal cohort study was designed and conducted between August 2019 and September 2021. In this chapter, the design and methods of the study are presented, whereas detailed information and the statistical procedure are described in the respective research articles included in this thesis.

4.1 Study Design

Four high-level youth football teams were recruited from German clubs. The four teams consisted of male Under-11, Under-15, and Under-19 teams and one female Under-17 team. In addition to football players from these teams, age- and sex-matched athletes playing basketball (males) and volleyball (females) at a similar level of play were enrolled as controls.
All athletes participated in a battery of neurocognitive, vestibulo-ocular, and postural control tests at the beginning of the season. Football players were tested at the start of the 2019-20 season (August 2019) or 2020-21 season (September/October 2020), whereas all control athletes were enrolled in the 2020-21 season and were therefore tested in September/October 2020. Immediately after the pre-season assessment, systematic video observation of the football teams was initiated and carried out throughout the whole season, with video recordings of every match and training session. Every header was analyzed with a standardized heading protocol. Following each season, neurocognitive and vestibular testing protocols were repeated in all athletes, and the standardized heading analysis was completed.

The study was conducted, and all data were collected in accordance with the declaration of Helsinki. Ethical approval was given by the ethics committee of the Westfalian Medical Board (2019-321-f-S), and the study was registered at the German Clinical Trial Register (DRKS00018923).

4.2 Participants

Inclusion criteria for participating teams and players were regular training and participation in official matches in one of the top three German junior leagues (Bundesliga, Regionalliga, Westfalenliga) of their respective age groups. Given that there was no league system for the Under-11, the youngest teams were included and assessed based on their regular training and competitions, such as friendly matches and tournaments. Participants with head injuries on the day of baseline testing and those with lower extremity injuries when testing postural control were excluded.

In total, 194 athletes were enrolled in the study, consisting of 135 football players (2019-20 = 86; 2020-21 = 49) and 59 control athletes without exposure to heading. The flow diagram of this study with reference to the research papers is presented in Figure 3.

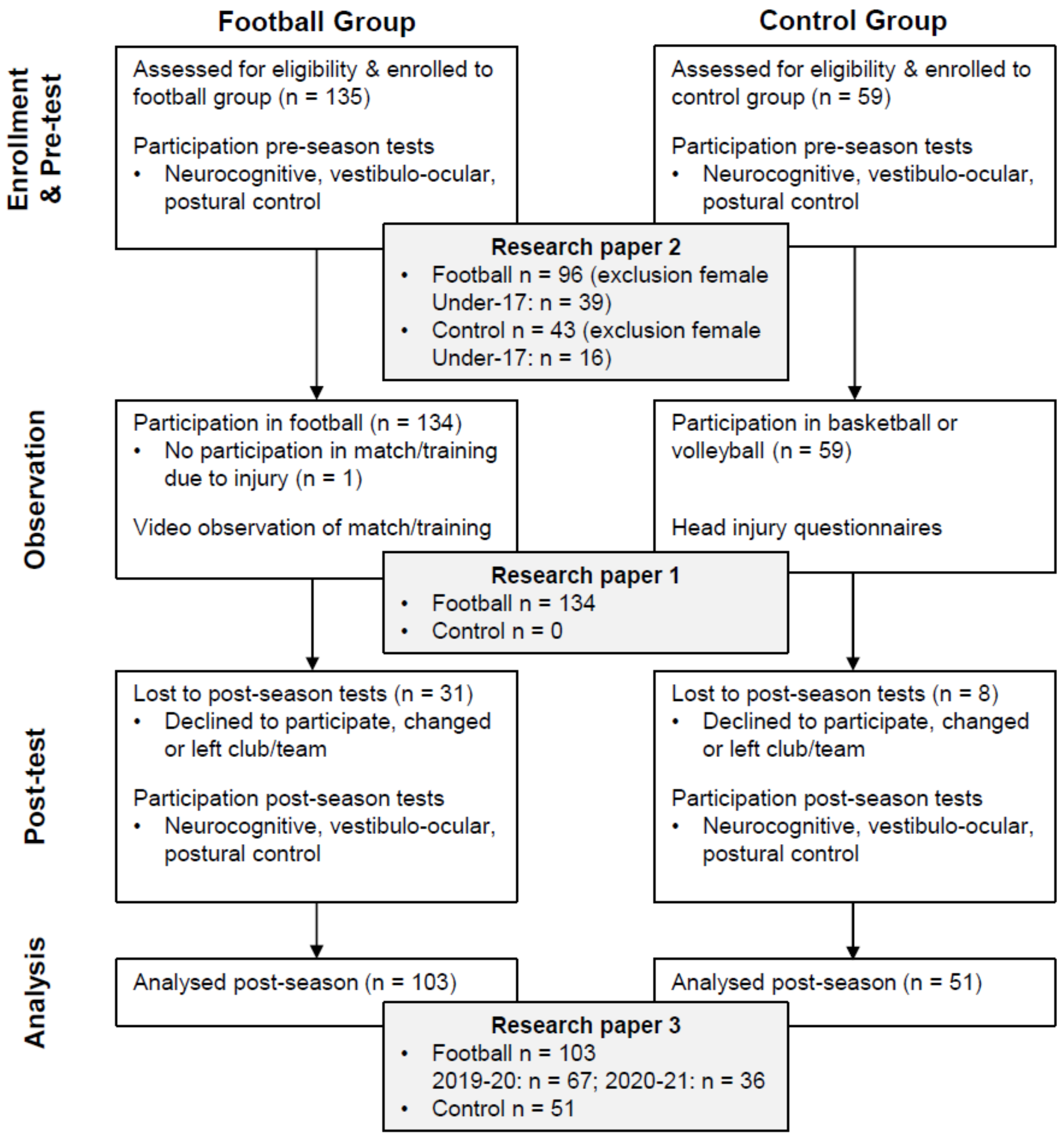

Figure 3 Flow diagram of the longitudinal cohort study with reference to research papers (modified from CONSORT 2010 [151]).

The study protocol pre- and post-season included the collection of demographics, medical history, and sports history, in addition to the testing of neurocognitive functions, vestibulo-ocular functions, and postural control from the participating football players and control athletes. At baseline, attention-deficit/hyperactivity disorder (ADHD) without the intake of medications was reported in one female football player, whereas other psychiatric or learning disorders have not been registered (research papers 2 and 3). Baseline characteristics of all football players and control athletes who participated in pre- and post-season assessments are displayed in Table 1. In these athletes, total age and the distribution of sex and age groups were similar between football and control athletes. The career length, individual study observation period, and history of concussion were significantly higher in football players than in control athletes (research paper 3).

Table 1 Demographic information and season characteristics of players assessed pre- and post-season (from research paper 3)

	Football 2019-20 (n = 67)	**Football 2020-21** (n = 36)	**Control** (n = 51)
Sex, n (%)			
female	24 (36)	9 (25)	15 (29)
male	43 (64)	27 (75)	36 (71)
Age at enrollment in years, mean (SD)	14.5 (2.5)	13.8 (3.2)	14.6 (2.6)
min-max	9.3-18.5	9.3-18.7	9.8-18.6
Player per age group, n (%)			
Under-11 male	13 (19)	14 (40)	12 (24)
Under-15 male	16 (24)	4 (11)	12 (24)
Under-17 female	24 (36)	9 (25)	15 (29)
Under-19 male	14 (21)	9 (25)	12 (24)
BMI, mean (SD)	19.9 (2.6)	19.5 (2.9)	20.1 (2.7)
Observation period in months, mean (SD)	10.6 (0.6)	9.7 (1.7)	9.6 (1.1)
Latency header to post-test in days, mean (SD)	138 (34)	14 (21)	
Migraine, n (%)	4 (6)	2 (6)	2 (4)
Concussion history, n (%)	17 (27)	2 (6)	3 (6)
Career length in years, mean (SD)	8.9 (3.1)	8.4 (3.0)	5.8 (2.4)

Note: Football 2019-20, football players included in the 2019-20 season; Football 2020-21, football players included in the 2020-21 season; BMI, Body Mass Index.

4.3 Testing Procedure, Video Observation, and Outcome Parameters

Pre- and Post-Season Testing

The following procedure of data collection was conducted either at the Sports Medicine Institute at Paderborn University or in the clubs' training centers. Demographic data, information on sports history, medical history (e.g., disease, medication intake, injuries), and previous brain injuries were captured from all athletes via questionnaire. Athletes under the age of 15 responded to questions regarding demographics, sports history, and a limited amount of health-related information. Their guardians provided disclosure concerning medical history and potential brain injuries.

Neurocognitive functions were assessed using the computerized, self-explanatory tool CNS VS. The core battery of seven established neuropsychological tests was performed individually (30 min) [152]. The vHIT (ICS impulse, Otometrics, Taastrup, Denmark) was used to quantify the VOR in all SCC by turning the participant's head rapidly and unpredictably in the lateral, anterior, and posterior plane (10 to 15 min). The lateral DVA was tested via the DVA test (NeuroCom InVision, Natus Medical Inc., Seattle, USA). In doing so, the athlete actively rotates their head to the left and right side, with a maximal velocity of 120 deg/s, while identifying the direction of the optotype "E" on display (15 min). The SET (NeuroCom VSR, Natus Medical Inc., Seattle USA) was implemented to measure postural control in six standing conditions with the eyes closed (double leg, single leg, tandem, each on firm and foam surface; 10 min).

The testing procedure is described in more detail in research papers 2 and 3. All tests were conducted by trained and experienced study staff to ensure objective, reliable, and valid test results. The order of neurocognitive, VOR, DVA, and balance testing differed between athletes (e.g., CNS VS – vHIT – DVA – SET vs. vHIT – DVA – SET – CNS VS). However, the testing order for each individual was the same between pre- and post-tests.

Video Observation

Every training session and match of the football teams was recorded by means of one to two high-definition video camcorders (Sony HDR-CX625, Sony Corp., Tokyo, Japan) with 1929 x 1080/50 p resolution at 25 p. Included in the definition of a match were all league, cup, friendly matches, and tournaments with the official rules of football (no futsal). Training included all scheduled, coach-directed training sessions carried out with the team. In addition, match warm-ups were classified as training.

The cameras were attached to tripods and placed on one side of the field near the middle line. Training sessions with more than one ball played at a time were recorded using two camcorders, with each covering one half of the pitch. To increase the reliability of the quantification of headers, the camera was moved by research personnel, if necessary, depending on the position of the players on the field.

A team of trained raters conducted a comprehensive analysis of every recorded header by a standardized heading protocol [57]. Besides the quantification of individual heading frequency, the characteristics of each header were analyzed. Headers were categorized, for example, as heading duel (with, without), flight distance before heading (< 5 m, 5 to 20 m, 20 to 50 m, > 50 m), and point of contact to head (frontal, parietal, occipital, temporal, facial). Detailed information on the heading analysis is provided in research papers 1 and 3.
The incidence of potential head injuries during the observation period was captured via video recordings, post-season, and regular in-season questionnaires (control athletes). As no athlete included in the post-season assessment suffered a concussive head injury during the observation period (research paper 3), data are not further considered in this dissertation.

Outcome Parameters

After the exclusion of invalid scores [153], the subject's raw scores of six neurocognitive domains (composite memory, psychomotor speed, reaction time, complex attention, cognitive flexibility, processing speed), assessed by the CNS VS, were considered based on previous investigations [154] and used for the cross-sectional and longitudinal analyses (presented in research paper 2 and 3, respectively). The VOR-gain value (eye movement velocity divided by head movement velocity) was assessed by the vHIT for quantification of the VOR. As a measure of DVA, the loss between static and dynamic visual acuity (DVA loss, in logMAR) was captured in the lateral plane. The composite sway velocity (in degrees per second) of all six stances was assessed by the SET as a measure of postural control performance.
The heading analysis revealed the individual number of total headers, the number and percentage of heading characteristics, and the individual heading IR per 1000 match/training hours as primary outcome measures. The inter-rater reliability for heading analysis was assessed by the intra-class correlation coefficient (ICC; one-way random).

5 Publications and Results

Three publications are considered for this dissertation. This section will provide an overview of the results from the included research papers. The first paper describes the frequency and characteristics of heading in football players of various youth age groups observed across two seasons in matches and training sessions using systematic video observation. The second publication provides findings from cross-sectional analyses of pre-season testing. Neurocognitive performance, vestibulo-ocular function, and postural control in youth football players are compared to functions of age-matched ball sports athletes with respect to age-specific differences. In the third article, associations between the individual, objectively assessed heading exposure and pre- to post-season changes in neurocognitive domains, the VOR, DVA, and postural control in youth football players are displayed in a longitudinal design.

5.1 Research Paper 1

Reeschke R, Haase FK, Dautzenberg L, Krutsch W, Reinsberger C. Training matters: Heading incidence and characteristics in children's and youth football (soccer) players. *Scandinavian Journal of Medicine & Science in Sports* 2023; 33:1821–1830. doi:10.1111/sms.14408

Heading is unique to football and vividly discussed in recent years regarding potential short- and long-term consequences on brain function and structure [8, 18]. These concerns about negative effects of repetitive heading resulted in restrictions on heading in youth football in single countries [12]. However, little is known about heading exposure in youth football, particularly in training sessions and over a longer period, such as a whole season. To evaluate the real magnitude of heading in youth football, this prospective longitudinal study aimed to describe exposure of heading in a cohort of children’s and youth football players over two seasons using standardized video analysis.

One of each of the following high-level male Under-11 (n = 29), male Under-15 (n = 28), female Under-17 (n = 39), and male Under-19 (n = 38) youth football teams were included in this study. All matches and training sessions of these teams were videotaped during the 2019-20 and 2020-21 seasons. The heading frequency and characteristics of headers were analyzed according to a standardized heading protocol. Individual heading IRs per 1000 match or training hours were compared between age groups as well as between match and training.

In total, 275 matches and 673 training sessions were recorded across an average observation period of 11(± 5) months. With excellent inter-rater reliability (ICC = 0.998 (95% CI 0.995-0.999)), 22921 headers were observed and analyzed in match play and training. The heading IR per player in matches was 1256 for Under-11 males, 1608 for Under-15 males, 1050 for Under-17 females, and 1966 for Under-19 males. In training sessions, the IR per player was 739 in Under-11 males, 2206 in Under-15 males, 1661 in Under-17 females, and 1419 in Under-19 males (Figure 4). Male Under-11 players had significantly lower IRs compared to Under-19 males in matches ($z = -2.732$, $p = 0.018$) and compared to all older teams in training sessions ($p < 0.01$). The number of headers played per training session ranged between 0 and 902. Most players headed up to two times per match hour or training, and no player performed more than four headers per match hour. In contrast to the number of headers in matches, five Under-15 males played five to eight headers per training on average.

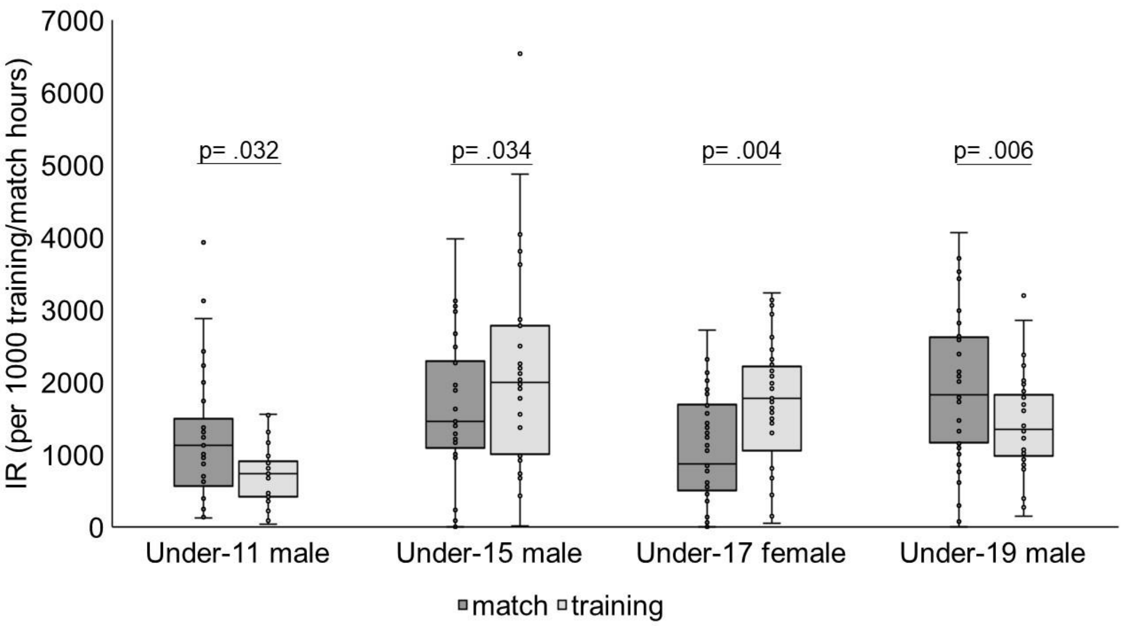

Figure 4 Heading incidence rate in match play and training sessions across age groups. Differences between match and training were analyzed by Wilcoxon test; IR, incidence rate (from research paper 1).

Most headers were played without heading duels (match: 58%, training: 91%). The flight distance of the ball before heading was predominantly 5 to 20 m (54%) in matches and under 5 m (65%) in training sessions. In matches, headers from distances greater than 20 m were rare in Under-11 players but increased with age. The contact point to the player’s head most frequently was at the frontal part (79% to 93%), whereas one-third of all headers in Under-11 males in matches hit the temporal, parietal, and occipital part of the head. Goalkeepers executed the lowest proportion of match headers (<6%), while midfielders (43%) and defenders (34%) exhibited the highest frequency of heading.

Author contributions

Rebecca Reeschke and Claus Reinsberger were responsible for the conception and design of the study. Werner Krutsch conceptualized the heading protocol. Rebecca Reeschke was responsible for the data collection over the study period. Rebecca Reeschke, Franziska Katharina Haase, and Lena Dautzenberg analyzed the data. Rebecca Reeschke and Claus Reinsberger wrote the paper. The draft of the paper was critically revised by all authors and all authors agreed to the final version.

5.2 Research Paper 2

Reeschke R, Dautzenberg L, Koch T, Reinsberger C. Neurocognitive performance, vestibulo-ocular function and postural control in youth male soccer and basketball players of different ages. *German Journal of Sports Medicine* 2024; 75:90-96. doi:10.5960/dzsm.2024.597

An assessment of multimodal functions, including neurocognition, VOR, or balance performance, is recommended [30, 138] and has already been implemented in the clinic and research of mTBI, particularly of SRC [141, 155]. However, the influence of sports and age on performance in those functions in adolescent athletes is not yet clear. Therefore, the aim of this cross-sectional study was to investigate sports-specific differences and effects of age on neurocognitive performance, VOR, DVA, and postural control in high-level adolescent football and basketball players.

In total, 139 male adolescent football (69.1%) and basketball players (30.9%) of the age groups Under-11 ($n = 45$, age: 10.4 ± 0.6), Under-15 ($n = 43$, age: 14.5 ± 0.6), and Under-19 ($n = 51$, age: 17.8 ± 0.7) were enrolled. All athletes participated in a test battery that consisted of the neurocognitive CNS VS and vestibular VOR, DVA, and postural control assessments. Athletes reported no diagnosed ADHD, learning or mental disorders, or medication intake with influence on the visual/vestibular system.
T-tests and Mann-Whitney-U tests (depending on normal distribution) revealed no significant differences between football and basketball players of the same age in any neurocognitive function ($p > 0.05$; composite memory: $d = 0.03$ to 0.18; other domains: $\eta^2 = 0.00$ to 0.04). In addition, the total VOR-gain ($d = 0.11$ to 0.63), lateral DVA loss ($d = 0.01$ to 0.52), and sway velocity ($\eta^2 = 0.00$ to 0.06; all $p > 0.05$) did not differ between sports. Logistic regression analyses, which adjusted for career length, concussion history, migraine, and height (only for sway velocity), confirmed these findings.

An Analysis of Variance (ANOVA) and Kruskal-Wallis tests revealed significant differences between age groups in all neurocognitive domains ($p < 0.001$, $\eta^2 = 0.11$ to 0.58). A better performance was found in older compared to Under-11 players in composite memory, psychomotor speed, reaction time, complex attention, cognitive flexibility, and processing speed ($p < 0.001$, $\eta^2 = 0.24$ to 0.71). A significant difference between Under-15 and Under-19 males was apparent only for cognitive flexibility, with higher scores in Under-19 compared to Under-15 players ($p = 0.003$, $\eta^2 = 0.14$).

Additionally, significant age group differences were found for the VOR-gain ($p = 0.018$, $\eta^2 = 0.06$), lateral DVA loss ($p < 0.001$, $\eta^2 = 0.11$), and sway velocity ($p < 0.001$, $\eta^2 = 0.36$). A lower mean VOR-gain ($p = 0.015$, $d = 0.58$) was observed in Under-11 compared to Under-15 males. The DVA loss ($p < 0.005$, $d = 0.68$ to 0.8) and total sway velocity ($p = 0.000$, $\eta^2 = 0.36$ to 0.46) were higher in Under-11 than in Under-15 and Under-19 players.

In summary, the findings of this study indicate that performance in neurocognitive functions, VOR, DVA, and postural control did not depend on sports in youth football and basketball players. Male players under the age of 11 showed lower neurocognitive and vestibular function performance than older adolescent athletes. Notable developmental changes between 10- to 14-year-old athletes may be relevant to account for an age-adequate performance representation.

Author contributions

Rebecca Reeschke and Claus Reinsberger were responsible for the conception and design of the study. Rebecca Reeschke was responsible for data collection. Lena Dautzenberg and Thorsten Koch significantly contributed to the collection of data. Rebecca Reeschke conducted the statistical analyses. Rebecca Reeschke and Claus Reinsberger wrote the paper. Lena Dautzenberg commented on previous versions, and all authors agreed on the final version.

5.3 Research Paper 3

Reeschke R, Dautzenberg L, Mund FK, Koch T, Reinsberger C. Heading is no homogeneous condition: Effects of different header types on neurocognitive and vestibular performance in youth soccer players. *Medicine & Science in Sports & Exercise* (submitted)

Repetitive head impacts, such as those resulting from heading, may cause deficits in neurocognitive performance as well as in visual and vestibular functions [16, 135, 137]. Particularly, potential consequences of heading on the developing brain of youth athletes are unclear, and further elucidation is needed. Consequently, the aim of this article was to investigate associations between the objectively assessed individual heading frequency and performance changes in neurocognitive and vestibular functions after one season in high-level youth football players. As long-distance headers have been found to be associated with cognitive performance [123] and headers played in duels can potentially result in higher force to the head (Chapter 2.2.3), the impact of these header types was subsequently analyzed.

In total, 103 football players and 51 control athletes aged 9 to 19 years were tested before and after the season in various neurocognitive domains, vestibulo-ocular functions, and postural control. After Bonferroni correction ($p < 0.008$), dependent t-tests and Wilcoxon tests revealed a significant improvement over the period of one season in all neurocognitive domains ($d = -0.39$ to 1.06, $p < 0.003$) but composite memory. These changes were apparent in football players included in the 2019-20 ($n = 67$) and 2020-21 ($n = 36$) seasons, as well as in control athletes. Also, the VOR-gain in football players included in the 2019-20 season ($d = -0.32$, $p = 0.01$) and sway velocity ($d = -0.35$ to -0.67, $p < 0.01$) significantly improved over the period of one season. No changes were found in VOR-gain of other groups and DVA loss. There was no interaction effect between pre- to post-season changes and age groups in any function, analyzed by mixed repeated measurement ANOVAs ($p < 0.05$).

A total of 16313 headers were observed in the 2019-20 season, with a mean of 204 headers per player. 3068 headers were observed in the 2020-21 season, with 94 headers per player on average. Twelve and ten percent of all headers were played in duels and with a flight distance of more than 20 m before heading, respectively.

In both seasons, spearman correlation analyses revealed no significant associations between the individual total heading frequency per player and calculated changes in any neurocognitive function, VOR-gain, DVA loss, and sway velocity (Table 2).

Table 2 Correlation between individual total heading frequency and changes from pre- to post-season in football players

		p-value	**r (95% CI)**
Neurocognitive function			
Composite memory	2019-20	0.85	0.024 (-0.226, 0.271)
	2020-21	0.82	-0.039 (-0.377, 0.307)
Psychomotor speed	2019-20	0.39	-0.108 (-0.347, 0.145)
	2020-21	0.38	-0.152 (-0.466, 0.195)
Reaction time	2019-20	0.28	0.133 (-0.118, 0.368)
	2020-21	0.59	-0.094 (-0.418, 0.252)
Complex attention	2019-20	0.53	-0.08 (-0.326, 0.176)
	2020-21	0.57	-0.098 (-0.422, 0.247)
Cognitive flexibility	2019-20	0.58	0.071 (-0.183, 0.316)
	2020-21	0.93	-0.016 (-0.352, 0.323)
Processing speed	2019-20	0.22	-0.151 (-0.384, 0.100)
	2020-21	0.95	-0.01 (-0.346, 0.329)
VOR-gain	2019-20	0.46	-0.094 (-0.339, 0.162)
	2020-21	0.11	-0.277 (-0.566, 0.072)
DVA loss	2019-20	0.79	0.033 (-0.218, 0.280)
	2020-21	0.74	0.058 (-0.290, 0.393)
Sway velocity	2019-20	0.56	0.074 (-0.182, 0.321)
	2020-21	0.75	-0.056 (-0.396, 0.297)

Note: CI, confidence interval; 2019-20, inclusion in the 2019-20 season; 2020-21, inclusion in the 2020-21 season

However, without a comparison for multiple testing, improvements in psychomotor speed were significantly lower with more headers played in duels (r = -0.255, 95% CI = -0.474 to -0.006, p = 0.04) and from more than 20 m flight distance (r = -0.299, 95% CI = -0.510 to -0.055, p = 0.02) in the 2019-20 season. In addition, a higher number of headers played in duels (r = 0.375, 95% CI = 0.043 to 0.632, p = 0.02) and from more than 20 m flight distance (r = 0.359, 95% CI = 0.025 to 0.621, p = 0.03) were significantly correlated with smaller improvements in reaction time in the 2020-21 season. These associations were small and only tend to be significant in the 2019-20 season (duels: r = 0.226, 95% CI = -0.022 to 0.448, p = 0.07; > 20 m: r = 0.230, 95% CI = -0.018 to 0.451, p = 0.06;

see Figure 5). No further correlations were found between heading characteristics and calculated changes in neurocognitive, vestibulo-ocular, or balance functions.

These findings demonstrate that improvements from pre- to post-season in neurocognitive domains and postural control in youth football players did not correlate with the total number of headers a player performed. However, the findings suggest the trend that the exposure to long-distance headers and those played in duels potentially revealed lower improvements over one season. The results may indicate that specific heading characteristics may be of interest in discussions about adverse effects.

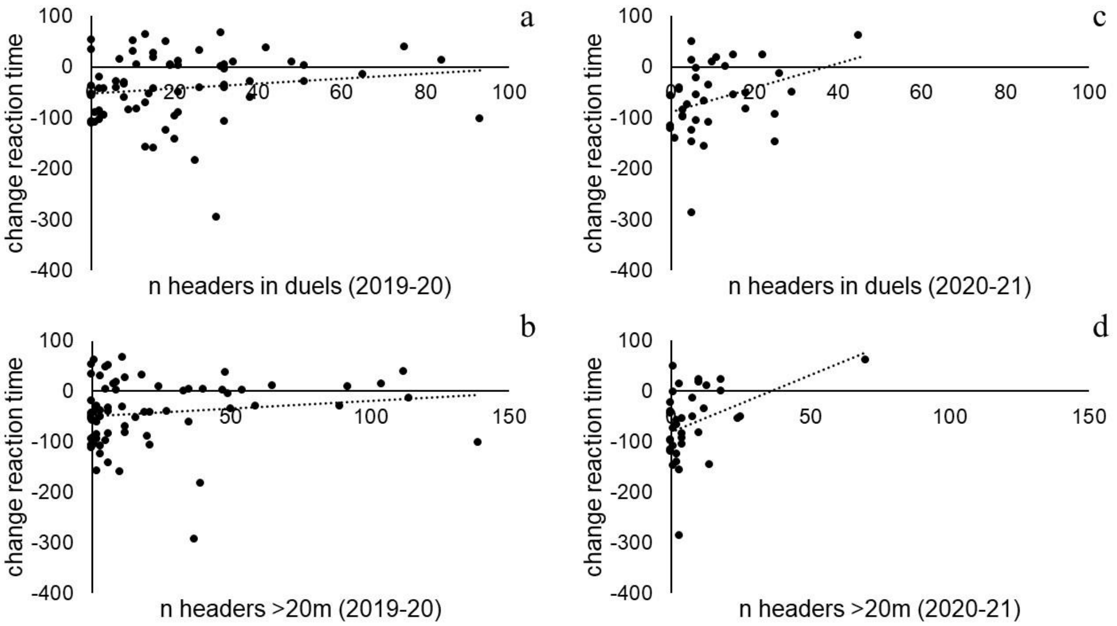

Figure 5 Correlation between individual change in reaction time and number of headers played in the 2019-20 and 2020-21 seasons in duels (a & c) and from > 20 m flight distance (b & d). Change scores represent the individual differences post minus pre. After exclusion of one outlier in the 2020-21 season, no significant, moderate correlations were found between change in reaction time and headers in duels (r = 0.319, 95% CI = -0.026 to 0.597, p = 0.061) and from > 20 m flight distance (from research paper 3).

Author contributions

Rebecca Reeschke and Claus Reinsberger were responsible for the conception and design of the study. Rebecca Reeschke was responsible for data collection. Lena Dautzenberg and Thorsten Koch contributed to the collection of data. Rebecca Reeschke and Franziska Katharina Mund analyzed the data. Rebecca Reeschke and Claus Reinsberger wrote the paper. The draft of the paper was critically revised by all authors. All authors agreed to the final version of the manuscript.

6 Discussion

The main objective of this thesis is to contribute to a better understanding of heading exposure and burden in youth football, as well as the consequences of repetitive heading on brain functions. The following chapter gives a brief summary and interpretation of the results provided in the three articles included in this thesis. In the first part of the following chapter, the frequency and characteristics of heading in German high-level children and youth football players, observed across two seasons in match play and training based on video analysis, are discussed. The second part of the chapter focuses on the neurocognitive, vestibulo-ocular, and postural control performance in football players compared to adolescent athletes playing different ball sports and whether individual heading exposure in football affects the aforementioned functions after one season.

6.1 Summary and Discussion of Findings

6.1.1 Heading Exposure in Youth Football

Research paper 1 shows that most of all headers were played in training sessions (n = 18892) compared to match play (n = 4029) in all surveyed youth teams, which is similar to previous study results [44, 54] and an indication that training plays a major role in assessing heading exposure in youth age. Training sessions make up the largest proportion of all football sessions, consequently influencing total heading numbers. However, even under consideration of the match/training exposure, the IR of Under-15 males and Under-17 females in training and maximum numbers of headers per training in all age groups clearly exceeded heading frequency in matches. Single training sessions that focused on heading training or included heading-intensive exercises revealed very high heading numbers. These sessions, which may have depended on the coaching style [156], have been an integral part of the representation of authentic football training and have influenced the total heading exposure. Accordingly, the upper range of headers played per training exhibited considerable variability between sessions (0 to 902 headers), confirming previous findings [54]. It cannot be ruled out that participation in this study may have influenced the coaching style and that the number of headers trained and played would have differed from headers in training outside of the study. However, over the period of the study, it can be assumed that coaches and players got used to video observation and that there was little to no alteration of training design.

In addition, it was found that heading exposure differs between youth age groups. The heading IR per player and frequency per session (research paper 1) increased with increasing age (for males) in matches and especially in training from male Under-11 to Under-15 players. Under-11 football players rarely headed the ball in match play and training. Differences between the ages can be explained by differing demands on the individual player due to lower field and ball sizes in Under-11, but also by the lower physical performance and technical requirements of younger players [157]. The finding of age differences and the heading frequency of different age groups in matches and partly in training in research paper 1 are comparable with previous studies [52, 54, 75, 158, 159], whereas heading incidences of Under-11 players in training (IR: 718) are significantly lower than in players of similar age in a large cross-sectional study (IR: 5007) [54]. This may be explained by the study design and the nature of a longitudinal study to represent a realistic composition of training contents (e.g., the frequency of heading drills) and, therefore, heading exposure over time. In contrast, participation in a cross-sectional “heading” study with the observation of one single training session may influence the coaching style employed. Consequently, coaches may be induced to implement more (or less) heading drills, and/or players may be tempted to head the ball more (or less) frequently.

Most of all players headed the ball a maximum of two times per match hour or training. Interestingly, some Under-15 males performed five to eight headers per training, accounting for one-third of all headers at this age. The individual differences in heading numbers between players in training, as previously described for matches [52], may also be explained by the varying demands and requirements of the players. For example, the player’s position was found to be a significant factor in determining the extent of heading exposure in both research paper 1 and previous investigations [66]. The findings of a higher heading number played in training compared to matches in general and a considerable variation in individual heading frequency in training indicate that training sessions with its individual heading exposure must be considered when assessing heading exposure in longitudinal studies, which, for instance, investigate potential effects of heading.

In addition to the assessment of heading frequency, headers were categorized in research paper 1. The quantification of headers in terms of their characteristics revealed that most headers, particularly those observed in training sessions, were played without

heading duels, from less than 20 m flight distance, and with the frontal part of the head. Headers were sparsely played in duels, especially in training sessions, which is in line with previous findings [54, 69]. So, the risk of an uncontrolled heading technique or head injuries due to contact with another player [28] is low. Headers performed after a flight distance of more than 20 m have been considered long-distance headers [160]. Those headers, potentially resulting in higher forces to the head than short-distance headers [70], were rarely played in Under-11 players and increased with age in matches. In training sessions, most headers were played from short distances of under 5 m, similar to findings of other studies [54, 123]. A frontal head impact location was predominantly observed in all age groups in match play and training, which is in line with other observed youth cohorts [54]. As described in Chapter 2.2, this can be an indicator of a well-prepared, coordinated sequence of body movements before contacting the ball and, thus, for a correct heading technique [63]. Consequently, the heading characteristics predominantly observed in this youth cohort may indicate that headers were performed with a relatively low impact magnitude to the head, as head impact kinematics were found to be related to the heading technique [161]. Interestingly, nearly a third of all match headers in Under-11 players were played with other parts of the head, like in previous findings [63]. Using the parietal or temporal region of the head may indicate an incorrect heading technique, potentially resulting from an unintentional head impact [54] or the player’s lack of experience and preparedness. These headers may have resulted in higher linear and rotational velocities of the head [63, 162] and, therefore, may be of interest to future studies and potential practical implications.
The adaptation of a correct heading technique is crucial for this complex skill. A good application of heading technique may potentially result in a reduction of head impact acceleration. Therefore, teaching the correct technique might be an aspect to consider when making heading recommendations. However, due to the low overall and individual heading frequency observed in adolescents under the age of 11, the number of headers executed poorly was consequently low. Additional research on prospectively and objectively observed heading exposure in various other cohorts and investigations of the relationship between heading characteristics and resulting kinematics on the head can add scientific value here.

With regard to research question 1 of this dissertation, the frequency of heading in youth football players was higher in training sessions compared to matches. It was very low in Under-11 players and increased with age. Furthermore, heading numbers differed individually, particularly in training sessions. The exact total heading frequencies and heading IRs in match play and training of different youth age groups are described in research paper 1. Most headers were played without heading duels, from a short flight distance, and with a frontal head impact location.

6.1.2 Impact of Heading on Neurocognitive Performance in Youth Players

Research paper 2 describes cross-sectional analyses of pre-season testing. Significant, primarily large differences between male age groups were found in all neurocognitive domains, with lower performance in football and basketball players aged under 11 compared to older adolescent athletes. In addition, longitudinal analyses in research paper 3 revealed an improvement of all domains except memory over ten to eleven months in adolescent football players and control athletes. These results confirm the assumption that neurocognitive functions notably develop with age in adolescence (see Chapter 2.3). Findings are in line with age group differences in memory, processing speed, and reaction time in 10- to 15-year-old athletes [152] and annual performance increases described for high-school athletes [21]. The potential developmental changes may be attributed to myelination of neurons and an increase in connectivity between brain regions at this age [88], during which a relationship between the development of white matter microstructure and executive functions has been described [163].

Not only age but also regular participation in sports is an influencing factor associated with beneficial effects on neurocognitive functions [2, 164]. The influence of football-specific demands on those functions, however, is debated but rather unknown, particularly in youth athletes [2, 94].

In research paper 2, the pre-season performance of high-level male football players was compared with that of basketball players, who had similar requirements and cognitive stimulation provided by the sporting environment but without intentional exposure to RHIs caused by heading. The results demonstrated no differences between athletes playing football and those playing basketball in any neurocognitive domain performance. This is consistent with investigations that presented no clinically significant differences in neurocognitive functions between adolescents engaged in contact sports and those who do not participate in contact sports [152]. The findings of this study indicate that playing football and the associated physical demands on players may not result in any discernible performance differences between youth football and basketball players when compared in cross-section.

Longitudinal analyses over one season, presented in research paper 3, showed that various neurocognitive functions of youth football players improved over one season, similar to changes in control athletes. As mentioned above, this finding possibly indicates a regular developmental effect. However, it is also necessary to consider the potential influence of practice effects, given the positive impact that physical activity has on neurocognitive functioning in children [164]. For instance, neurocognitive performance has been found to be better in youth athletes compared to nonathletes or a norm sample [2, 165] and in high-level athletes compared to those active on a low performance level [82]. Participation in sports and, consequently, the learning of complex motor skills and techniques may have resulted in structural adaptations within the brains of the athletes tested in this study. This assumption is based on the finding that learning to juggle has led to an increase in grey matter volume, which indicates that physical training can induce cortical plasticity [166].

To investigate the impact of heading on these changes, a subsequent investigation revealed no association between the player's individual total heading frequency and improvements in any neurocognitive domain after one season. There is only weak evidence for a clear relationship between heading exposure and function impairments [16, 18]. The results of this study confirm the current state of literature, where cognitive function was not negatively affected by objectively assessed exposure to heading in most of all studies, which mainly included youth football players [18]. Similar to the results of research paper 3, no effect of the total heading frequency on neurocognitive parameters has been found after a few training sessions [123] or a weekend football tournament [61] in youth players. With data collected objectively during both match play and training over the course of several months, this study, however, represents an inaugural prospective investigation into the impact of heading exposure. Furthermore, by including appropriate control athletes, this study was able to overcome some of the methodological limitations observed in similar studies [16].

Neurocognitive pre-season scores and improvements over one season in football players were similar to those of ball sports athletes without exposure to heading (research papers 2 & 3). In combination with the absence of any correlations between the total heading frequency and changes in performance, it may be concluded that the individual overall heading exposure may not lead to neurocognitive impairments in high-level adolescent football players after one season. Nevertheless, it is possible that potential functional changes resulting from cumulative head impacts may not manifest within the span of a single season. Therefore, further investigations on the impact of realistic, individual exposure to headers over a more extended period in (youth) athletes are necessary for a complete understanding of potential effects of these repetitive head impacts.

However, specific heading characteristics, such as the flight distance before heading, are discussed to affect outcomes, as changes in neurocognitive functions have been identified, especially in association with higher numbers of headers played from longer distances [123, 125, 137]. Therefore, the effects of different header types may be of great interest to future investigations. In research paper 3, not only the influence of the total number of headers but also of headers played in duels and from a distance of more than 20 m on pre- to post-season changes were analyzed. It was found that a higher number of heading duels and long-distance headers was associated with a lower improvement over one season in psychomotor speed (in football players from the 2019-20 season) and in reaction time (in football players from the 2020-21 season), showing small to moderate effects. These results are in line with those presented by Koerte et al. [123], who observed that the improvement in response time in youth players over one season was lower with more long-distance headers played. In addition, neurocognitive changes have been shown to be greater in magnitude after long-distance headers than after short-distance head impacts [125]. A potential explanation for this finding is that headers played from longer distances of more than 10 m may result in higher linear and angular accelerations compared to those from short distances [70, 167].
Similarly, head impact kinematics were higher for jumping than for standing headers [75, 167] and for those with head-to-head contact [162]. Both characteristics, headers played in jumps and with contact to another player, can be found in heading duels and have been described to be predominant activities causing head injuries [28, 56]. In addition, most of the head impacts (except those caused by heading itself) with visible force transfer to the brain have been recorded after heading duels [168]. So far, studies investigating the influence of heading duels are missing. A previous study revealed that female football players who headed more high-acceleration impacts demonstrated lower visual memory performance, whereas visual motor speed and reaction time were not affected [137]. In 9- to 11-year-old tackle football players, neither the cumulative impact exposure nor high-intensity impacts were found to be a predictor of changes in any neurocognitive domain over three seasons [131]. Given the paucity of data and evidence, future research is required to investigate the influence that heading duels and long-distance headers have on neurocognitive performance in youth football players.

As the correlations between specific heading types and performance changes only appeared to be significant without the correction for multiple comparisons, findings need to be interpreted with caution. Neurocognitive functions like reaction time and psychomotor speed, which showed a trend to be affected following a higher number of heading duels and long-distance headers, can be impaired following concussions. Impairments after SRC may be caused by multiple, complex pathophysiological processes in the brain [34, 169], including an initiated "[…] neurotransmitter and metabolic cascade, with possible axonal injury, blood flow change and inflammation […]" [30]. However, the (patho-)physiological mechanisms that describe potential effects of RHIs or heading remain unclear. Underlying mechanisms, such as structural brain alterations, are largely unknown and should hence be targeted in future research. Overall, it must be noted that improvements in most of all neurocognitive domains (such as complex attention, cognitive flexibility, and processing speed) were not found to be related to the individual total number or the number of specific characteristics of headers performed by an athlete.

The influence of specific heading characteristics on reaction time was identified predominantly in the 2020-21 season. Findings differed between the analyzed seasons and cohorts, which may be explained by time-related aspects, specifically the time interval between the last football sessions and post-testing. Due to the COVID-19 pandemic, training sessions and matches in the 2019-20 season were canceled in March 2020, and post-tests could only be conducted after an average latency of 138 days from the last recorded header. In the 2020-21 season, post-tests were conducted within a few days of the last recorded match or training session, with a mean latency of 14 (SD = 21) days (research paper 3). Consequently, the interval between the last match or training, which involved potential headers, and the subsequent testing was considerably longer in the 2019-20 season than in the 2020-21 season.
In a study conducted already 20 years ago, neurocognitive performance was found to be significantly lower in youth and young adult football players who reported the highest heading estimates during a time span of seven days before testing [60]. It has been assumed that the temporal interval between impacts is a significant factor pertaining to the risk of head injuries [170]. It is conceivable that adaptations in neurocognitive functions related to heading may be reversible. For instance, a reduced cognitive function has been observed immediately following a bout of twenty headers, which normalized within 24 hours [127]. Therefore, the shorter time between the last headers

and post-season assessment in 2020-21 may explain the larger effects on the correlation between smaller improvements in reaction time and more headers played in duels or from longer distances. Consequently, any potential performance impairments in reaction time resulting from heading during the 2019-20 season may have recovered by the time of the post-test. However, the temporal development of potential behavioral changes due to heading, its possible recovery, and the influence of the temporal interval between head impacts and performance testing remains poorly understood. In a recent study of adolescent football players, findings have demonstrated that the effects of long-distance headers on cognitive performance lasted longer than those of short-distance headers [125]. The study additionally revealed that adverse effects of long headers on executive functions may not be mitigated and may even persist beyond a period of one month. After suffering SRC, youth athletes take around 15 days to recover from symptoms, which is longer compared to male adults [171]. Transferred to possible effects of subconcussive head impacts, it may be assumed that a potential recovery time is higher in youth players compared to adults.

It is important to note that in the 2020-21 season, one football player performed a total of 45 heading duels and 70 long-distance headers. These numbers are considerably higher than the mean frequency of headers assessed (n duels = 14; n > 20 m = 8; research paper 3). However, substantial heterogeneity in the individual heading frequency between youth players is described in research paper 1 and previous investigations [52]. Given a heterogeneous heading frequency and the fact that this observation represents the actual exposure to heading in youth, there was no rationale to exclude this athlete. Nevertheless, when this “outlier” was excluded (analysis of players with less than 40 long-distance headers only), the relationship between the change in reaction time and heading duels or long-distance headers disappeared to be significant.

The association between less improvement in psychomotor speed and a bigger number of heading duels or long headers was observed exclusively in the 2019-20 season. This finding is unlikely to be explained by the hypothesis of regeneration time, given the long latency between potential headers and post-tests in this season. The total number of headers was significantly higher in the 2019-20 season (n = 16313) than in the 2020-21 season (n = 3068) due to the higher number of recorded matches and training sessions (research paper 3). Correspondingly, the number of heading duels and long-distance headers was higher in the 2019-20 season, and it is possible that this factor may have caused this season-specific effect. As correlations have been found to be poor to moderate, the (clinical) significance of the results is unknown.

It can be concluded that the total amount of headers was not associated with pre- to post-season changes in neurocognitive functions. In contrast, it can cautiously be hypothesized that the play of more high-impact headers, such as headers played in duels or long-distance headers, may have an impact on (the development of) single neurocognitive functions in youth football players. As suggested in a previously published study [123], improvements observed over time in youth players, potentially of developmental nature, may be suppressed by cumulative effects of high-velocity impacts.
However, it is not possible to exclude the possibility of a mixing bias to the extent that headers played in duels have also been played from long distances. Further evaluation with detailed investigations of heading characteristics in youth players is needed for a comprehensive understanding. Future studies that examine types of headers, which potentially reveal higher forces to the head, would help to better understand the impact of specific heading characteristics on neurocognition. It may be subsequently beneficial to investigate potential effects of regeneration and to consider the incorporation of additional testing following an interval of no exposure to heading in future studies. Furthermore, the periodization of heading within the observed season and the individual number of headers played in the sessions preceding testing should be taken into account in future studies, given that there was a significant disparity in the number of headers per training session (ranging from 0 to 902, research paper 1).

6.1.3 Impact of Heading on Vestibulo-Ocular and Postural Control Performance in Youth Players

Cross-sectional analyses of pre-season data revealed significant medium to large age group differences in terms of VOR-gain, DVA loss, and sway velocity, with males aged under 11 years performing poorer than older football and basketball players (research paper 2). The findings underlying this thesis corroborate the hypothesis that vestibular functions evolve with age in adolescents as the brain continues to mature, and for example, sensory integration improves (Chapter 2.3) [108]. Similarly, research paper 3 demonstrates an improvement in postural control over the course of one season in football players and control athletes. Age group differences and longitudinal improvements in postural control [20] may be explained by the development and maturation of biomechanical constraints, sensory and movement strategies, and cognitive capabilities in youth [108]. There was no appreciable change in vestibulo-ocular parameters from pre- to post-season (research paper 3). This is in accordance with previous research, where VOR and DVA values have remained stable across youth [172], whereas it has to be noted that functions may take longer than a few months to show changes.

The extent to which sports participation influences vestibular functions is likely complex and not fully understood so far. A better DVA and reduced postural sway have been observed in athletes compared to individuals who do not engage in any sports and in athletes performing on a higher level of sports [107, 173]. This suggests that participation in sports may confer benefits. However, there is public concern regarding the extent to which football and its demands, like repetitive heading, have a (potentially adverse) impact on these functions, leading to studies in this field [65, 94].
Cross-sectional comparisons between sports in research paper 2 demonstrate no differences between male youth athletes playing football and those playing basketball in VOR gain, DVA loss, and sway velocity. A previous study supports these results by showing that functional VOR performance did not differ between football players and other athletes [174]. In contrast, current investigations from Tarnutzer et al. showed slightly higher VOR gains in football compared to ice hockey players [94]. However, as it was possible for all athletes in the study underlying this dissertation to move freely without the need for protective gear with similar playing styles in their respective sports, visuo-vestibular performance strategies may not differ much between ball sports groups thus leading to similar test results in football players and other athletes. The findings on postural control are consistent with previous literature, which found no sports-specific differences in postural stability assessment in adolescent football players compared to athletes of other sports [175]. The cross-sectional comparison of football and basketball players revealed no discernible differences in performance or pathological outcome values. Therefore, it may be suggested that participation in football is unlikely to lead to impairments in vestibular functions after one season in a youth cohort.

As presented in longitudinal analyses in research paper 3, vestibulo-ocular functions mainly remained stable in all athletes, whereas postural control values improved over the course of one season in both football and other ball sports players. In addition to the

development of postural control caused by aging [20], participation in high-level sports may have contributed to improvements in postural control [107].
A subsequent examination of the impact of heading on the pre- to post-season changes revealed no significant associations between the individual total number of headers and performance changes in VOR and postural control. This finding is consistent with the results of previous studies that found no effect of playing football or repetitive heading on vestibulo-ocular parameters in youth football players [94, 128]. Based on the presented findings, the reduction in sway velocity from pre- to post-season in football and other ball sports players is likely to be explained by factors other than heading exposure, such as developmental processes in adolescent athletes [108] or a practice effect [106]. Previous research findings regarding the effect of heading on postural control measures are disparate. A systematic review describes significantly worse postural control performance, as measured by the use of instrumented tools, following a heading intervention (10 to 12 headers in 10-12 min) when compared to a control group in three out of eight studies. However, in the majority of studies, no association between heading and altered postural control was observed [132]. Despite the evidence that the vestibulo-ocular function and balance can be impaired in children and adolescents following SRC [36], no evidence for a cumulative effect caused by the overall exposure to heading or pathological values after one season was found in research paper 3. It is important to note that in previous studies, the absence of control groups, a potentially limited realism of football scenarios in intervention studies, and the lack of analysis of impact characteristics present themself as significant limitations. These factors have been largely overcome in the present study.

Besides the total heading frequency, factors such as the flight distance of the ball before heading are discussed to affect postural control measures [132]. It has been demonstrated that headers played in jumps [167] and with head-to-head contact [162] are associated with higher accelerations. Furthermore, the linear and angular accelerations experienced when executing headers were likely to be greater when the ball was played from a greater distance [70, 167]. Therefore, the impact of headers played in duels and from a flight distance exceeding 20 m on the vestibular system was additionally analyzed in research paper 3. The results indicate no association between a high number of such headers, which potentially exert higher forces to the head, and changes in any vestibulo-ocular and postural control parameter. The influence of specific headers on vestibular parameters has even been less extensively investigated than the impact of the total heading frequency. Confirming the findings of research paper 3, repetitive head impacts resulting in higher intensities did not lead to vestibulo-ocular changes in nine- to eleven-year-old male tackle football players [131]. In contrast, the maximum rotational acceleration correlated with pre- to post-season DVA loss changes in a small sample of young adult lacrosse players [176]. However, as VOR variables have not changed significantly over the course of the lacrosse season, the extent to which an influence was exerted may be open to debate. As the exposure to heading in football differs from head impacts in players of other sports, future studies that assess the impact of heading characteristics on vestibulo-ocular functions in larger samples of youth football players may add valuable evidence.

In line with no correlation observed between different heading characteristics and postural control in research paper 3, a previous study in young tackle football players revealed that sustaining a minimum of one high-intensity head impact per season did not result in balance changes [131]. While a greater exposure to high acceleration impacts resulted in tandem gait changes from pre- to post-season testing in women football players, other balance measures have not been affected by headers, confirming the presented findings [137]. This study represents a preliminary step towards bridging the gap between prospective studies in youth athletes of other sports and studies in adult football players. Future research should focus on prospective monitoring over a longer time span and the examination of the effects of specific heading characteristics on vestibular functions in youth football players.

In conclusion, there were no sports-specific differences (research paper 2), the development of vestibulo-ocular and balance functions was similar between football players and control athletes, and no associations between heading and vestibular performance (alterations) were found (research paper 3). Accordingly, there is no reason to assume that heading may have had an impact on the vestibulo-ocular function and postural control over one season. Given the lack of research, future studies are required to further investigate the influence of specific heading characteristics that may result in higher forces to the head. This would assist in the confirmation of the presented findings and the development of a better understanding on the impact of heading on vestibular functions.

Research question 2 of this thesis aimed at examining how neurocognitive performance and vestibular functions differ between youth football players and athletes of other ball sports and how functions differ between age groups. The neurocognitive domains, VOR, DVA, and postural control of youth football players did not differ from those of age-matched basketball players. Football and basketball players aged under 11 performed considerably lower than older athletes in neurocognitive functions, VOR, DVA, and postural control (research paper 2).

Regarding research question 3, for most of all neurocognitive domains and performance in postural control, an improvement was found from pre- to post-season testing in youth football players in both seasons. The vestibulo-ocular function mainly remained stable over the period of one season. Given that improvements in performance were comparable to those of athletes engaged in other ball sports, this finding may be attributed to developmental and/or practice effects. There was no impact of the total heading frequency of a football player on any of the analyzed functions. However, a high number of specific header types, which potentially reveal higher forces to the head, was associated with changes in neurocognitive performance. More precisely, the more headers played in duels or from more than 20 m flight distance, the less improvement over one season was observed in psychomotor speed (in football players from the 2019-20 season) and in reaction time (in football players from the 2020-21 season). There was no impact of these header types on any other neurocognitive or vestibular parameters (research paper 3).

It needs to be considered that the (developing) brain is able to change and adapt to a variety of environmental experiences [177]. Due to the plasticity of the brain, learning to head the ball correctly as a complex motor skill may lead to structural brain alterations, which can be reversible and disappear after a period without practice [166]. The extent to which a potential cumulative effect of heading that leads to brain damage and may result in long-term sequelae is reversible needs to be further evaluated.
In general, all athletes included in this study were healthy and active in high-level sports. Pre- and post-season test values were not pathological and comparable to norm values [139]. Therefore, the clinical relevance of the trend towards an association of headers with potentially high impact and changes in neurocognitive performance over the observation period is uncertain. Changes were not associated with the overall exposure to heading. Nevertheless, the findings indicate the necessity for further detailed investigations of the impact that particularly specific heading characteristics may have on neurocognitive outcomes.

6.2 Methodological Considerations and Guidelines for Future Studies

This study addresses several shortcomings of previous studies [16, 18] by employing a prospective, high-quality video-based, and individual assessment of heading exposure in matches and training sessions. For the prospective longitudinal investigation of male and female youth football players covering a large age span, an appropriate control group was included. Besides these strengths in the study design, some aspects need to be considered regarding the generalizability of results, limitations, and potential adaptations in future study replications.

As this study aims to investigate the exposure and impact of heading, football players were included and observed. Therefore, the findings cannot be generalized and applied to head impact exposure and the influence of RHIs in other sports. Diverse ages of high-level youth athletes were represented in this study, whereas amateur or elite adult football players were not considered. This limits conclusions that can be drawn for other age groups or levels of play. Even transferability to other teams of the same age and level of play is limited, as the country of residence [54] and coaching style [156] may be influencing factors on the exposure to heading.

In total, 29% of athletes included in this study were females, representing only Under-17 players due to limited regional availability of high-level football athletes. In some way, this contributes to a realistic distribution of high-level youth football players, with fewer females and a higher percentage of males being active in football [1]. A potential explanation for the limited availability of females is that in several (German) regions, there are only a few players in general and a great inter-individual disparity in the level of play among younger than Under-17 teams. Players over 17 years of age often are included in adult teams. Future research may help in the assessment of heading exposure and its influence on brain health in additional female youth age groups.
The inclusion of appropriate control athletes is mandatory in future studies. To control for the effect of age, exercise level, and participation in sports over the period of one season, athletes engaged in team-based ball sports without intentional exposure to regular head impacts (basketball and volleyball) were additionally included in this study. Given that the nature of volleyball as a ball-return game differs from that of football, sports in Under-17 females are not ideally comparable.

The study, particularly the data collection, was influenced by restrictions during the COVID-19 pandemic. A major consequence was the reduced number of observed matches and training sessions, particularly in the 2020-21 season, caused by cancellations of sporting events and the cessation of team-based training activities starting in March 2020 [178]. Consequently, the previously described gap of 138 days on average between the last headers performed and post-season assessments in the 2019-20 season (July 2020) was another pandemic-related outcome. It limited the informative value regarding the influence of heading during one season. Simultaneously, it allowed for an explorative comparison between seasons with disparate latencies between heading and testing, and for a preliminary description of potential regenerational effects. Furthermore, the COVID-19 lockdown(s) may have influenced the health of players. It has been described that the COVID-19 lockdown had an impact on body composition parameters (e.g., increase in fat mass) in German high-level youth football players [179], whereas several physical abilities have not been affected in professional players [180]. How far changes in the behavior of athletes (e.g., social withdrawal, a limitation to home-based training) have influenced neurocognitive and vestibular functions in this study is not clear.

During the data collection, it was not possible to blind researchers for the sports and age of participants. Additionally, researchers were not blinded throughout the analysis of heading and neurocognitive/vestibular data. For the evaluation of neurocognitive performance, six neurocognitive domains have been selected for analysis based on previous investigations [154], whereas the impact of heading on further domains remains unknown. Outcome data on health and sports history of athletes were self-reported. Therefore, outcomes such as migraine, concussion history, or career length may have been vulnerable to recall bias [181]. To face this issue, considering the young age of participants, questions were partly answered by parents in the young age groups.

With one to two teams per age group included in this study, it was difficult to analyze factors such as the player’s position, concussion history, or lifestyle, which potentially influenced the exposure to different heading types and neurocognitive/vestibular outcome measures. A larger sample size in future investigations would facilitate the conduction of (subgroup) analyses. However, it is necessary to consider that the field position in children of the youngest age group is less predetermined and may switch between matches.

Additionally, expanding the sample size in future studies would be beneficial to reduce the influence of singular players (performing a high amount of specific headers) on investigations on effects of heading and thereby increasing the validity of results.

For this study, the impact of heading was analyzed by conducting correlation analyses of the heading frequency and the difference between the values assessed pre- and post-season. This approach has proven to be feasible as an explorative analysis of heading characteristics. Future investigations may benefit from statistical analyses, such as regression models, which include potential influential factors as co-variables, in addition to heading (type) numbers.
Based on literature [167], it was assumed that headers played in duels or long-distance headers may result in the exertion of higher accelerations to the head when interpreting the study results. However, no objective measurements of the head impact magnitude, such as accelerative forces, have been taken.

Post-tests were conducted after each of the two seasons of observation, whereas players have not been followed for further seasons or years. Whether this period is long enough to reflect alterations caused by headers in youth football players may be open to debate. It is unknown how many impacts are necessary and how long it takes until potential alterations related to heading appear as behavioral impairments in neurocognitive, vestibulo-ocular, and balance functions. Further studies over a longer period of observation (ideally covering the entire career or lifetime of a player) are mandatory to confirm the findings of this study and would provide insight into the potential long-term impact that heading exposure might have on neurocognitive and vestibular functions over a large age span in youth and adult football players.

6.3 Towards Practical Implications

The findings of this study may contribute to implications for practical application. In general, no influence of the overall heading frequency on neurocognitive and vestibular functions over one season has been observed (research paper 3), and further evidence is required to determine the influence of heading in youth football on (long-term) brain health. However, certain potential risk factors associated with heading may already be mitigated in order to reduce a possible risk for brain health. Age may be one of those factors. Headers in the youngest age group tested in this study were performed with minimal frequency and potential low impact intensity compared to older groups, while a third of all headers in matches in Under-11 males was played with other than the frontal part of the head and, therefore, potentially with improper technique (research paper 1). As heading is a complex skill to learn (Chapter 2.2) and an improper technique may lead to an exertion of higher acceleration forces to the head [162], it may be justifiable to introduce some type of low-impact heading technique training at younger ages already. In contrast, there would be no opportunity for young players to learn the correct heading technique in the event of a heading ban. Another potential strategy for reducing the prevalence of improper heading technique is to decrease the number of match headers, for example, by introducing small-sided games [18].

In general, this study suggests that focusing on headers in training sessions may be more important than only considering headers played in matches, as players engaged in a significantly greater duration of training sessions, and a higher number of headers were played during training than in matches. Additionally, attention should be given to high inter-individual variability of heading exposure in training due to singular (Under-15) players presenting a high individual heading amount (research paper 1). Training sessions provide a variety of opportunities to exert control over the players' heading behavior, as training drills depend on the instructions given by the head coach [156]. Accordingly, it is possible to regulate the individual exposure to heading duels and headers played from a distance of more than 20 m in practice, as well as the periodization of heading and regeneration times between heading-intensive sessions. Individual football associations, such as the German Football Association, have already implemented heading guidelines addressing the burden of long-distance headers in youth football [13, 15]. Overall, the practical implications of the findings presented in this thesis with respect to recommendations partly remain unclear and require further investigation.

7 Conclusion and Outlook

This dissertation and included research papers contribute to a more comprehensive risk assessment of heading in youth football by describing the frequency and characteristics of heading in match play and training and by increasing the knowledge about the impact of individual heading exposure on neurocognitive, vestibulo-ocular, and postural control functions.

Heading exposure, especially in training sessions, is highly individual between players and between age groups, with a very low incidence in the Under-11 age group. Given that most headers were played in training sessions, this study suggests that considering football training is essential for the design of future studies and age-specific heading recommendations.

The study findings indicate that there was no impact of the participation in high-level youth football and of the overall heading frequency a player is exposed to over the period of one season on improvements in neurocognitive, vestibulo-ocular, and postural control functions. A potential age-related performance increase across the observation period should be considered when investigating the possible impact of heading in adolescent athletes.

This thesis supports the concept of heading as a non-homogeneous condition, with different header types that need specific addressing in future studies on heading exposure and its impact, and in recommendations for heading. The results suggest that even specific headers, which may result in high-intensity impacts to the head, did not influence improvements in the majority of neurocognitive domains and vestibular functions. However, a trend was detected according to which specific neurocognitive domains (reaction time and psychomotor speed) may be affected by headers played in duels and from a flight distance of more than 20 m. Singular players performed a comparatively high number of high-impact headers. Conversely, it is possible that these findings may be somewhat mitigated when headers were played without duels, from a short flight distance, and with the frontal part of the head, as observed in the majority of players tested and, particularly by the youngest age group.

The results of this study may inform the drafting of heading recommendations (for training), in which the player's age, individual variability, the types of headers, and potential regeneration times should be considered. Additionally, findings may be utilized in the development of coaching strategies and players heading risk profiles.

In future research, it will be important to extend the understanding of heading exposure and its impact on female youth players of diverse age groups. Furthermore, and based on the findings of this dissertation, prospective longitudinal studies assessing various seasons should focus on the impact of specific header types (particularly of high-impact headers) on behavioral functions over a longer observation period. The impact of heading duels and long-distance headers on specific neurocognitive functions differed between both included seasons. Due to the possible explanation by an effect of recovery in the days prior to testing, the periodization of heading and the influence of regeneration times after the exposure to (high-impact) headers should be investigated in additional studies.

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9 Original Research Articles

Reeschke R, Haase FK, Dautzenberg L, Krutsch W, Reinsberger C. Training matters: Heading incidence and characteristics in children's and youth football (soccer) players. *Scandinavian Journal of Medicine & Science in Sports* 2023; 33:1821-1830. doi:10.1111/sms.14408

Reeschke R, Dautzenberg L, Koch T, Reinsberger C. Neurocognitive performance, vestibulo-ocular function and postural control in youth male soccer and basketball players of different ages. *German Journal of Sports Medicine* 2024; 75:90-96. doi:10.5960/dzsm.2024.597

Reeschke R, Dautzenberg L, Mund FK, Koch T, Reinsberger C. Heading is no homogeneous condition: Effects of different header types on neurocognitive and vestibular performance in youth soccer players. *Medicine & Science in Sports & Exercise* (submitted)

Received: 18 January 2023 | Revised: 3 April 2023 | Accepted: 15 May 2023

DOI: 10.1111/sms.14408

ORIGINAL ARTICLE

WILEY

Training matters: Heading incidence and characteristics in children's and youth football (soccer) players

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Funding information
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Abstract

Objective: Concerns about short- and long-term consequences of repetitive heading contributed to heading restrictions in youth football in some countries. This prospective longitudinal cohort study aims to describe heading exposure in children's and youth football over two seasons using standardized video analysis.

Methods: All matches and training sessions of a male Under-11 ($n=29$), Under-15 ($n=28$), Under-19 ($n=38$), and female Under-17 ($n=39$) team were videotaped during the seasons 2019–2020 and 2020–2021. Heading frequencies and characteristics were analyzed. Individual heading exposure is presented as average incidence rates (IR) per 1000 match/training hours.

Results: In 275 matches and 673 training sessions, 22 921 headers were observed. Heading IR per player in matches was 1256 (Under-11 m), 1608 (Under-15 m), 1050 (Under-17 f), and 1966 (Under-19 m). In training sessions, IR per player was 739 (Under-11 m), 2206 (Under-15 m), 1661 (Under-17 f), and 1419 (Under-19 m). Five Under-15 males headed the ball five to eight times per training on average. Most headers were performed without heading duels. Flight distance was predominantly 5–20 m (54%) in matches and <5 m (65%) in training. While head impact location most frequently was at frontal areas, one-third of all headers in Under-11 in matches hit temporal, parietal, and occipital parts of the head.

Conclusion: Heading incidence was low in the youngest age group, whereas (predominantly five) Under-15 males showed very high heading exposures in training. In assessment and regulation of heading burden, training sessions and individual heading behavior should specifically be addressed. Recommendations for heading the ball in practice should account for individual and age-related differences.

KEYWORDS

adolescent, brain injury, child, repetitive, soccer

Trial registration DRKS: DRKS00018923.

1 | INTRODUCTION

The intention to use the head to play and control the ball is unique to football.[1] In recent years, short- and long-term consequences and effects on brain function and structure of playing football, especially concerning traumatic brain injuries and repetitive heading, are vividly discussed.[2–5] Brain alterations and impaired cognitive function regarding heading in adults and adolescents were described in some studies,[6–8] but no overall effect has been conclusively described.[2,9,10] Various methodological approaches to investigate acute and chronic neurocognitive effects of heading have been used,[4] but causality of repetitive head impacts due to heading and effects is often inconclusive.[9,10] Data are especially sparse in children and youth players.[10]

The Football Association of England has recently published guidelines and recommendations on heading in youth football.[11] A review concluded that youth football players head the ball at a low frequency that increases with age and is influenced by sex.[10] However, a wide variation of heading burden between studies regarding total heading numbers, typically recorded in matches, and head impact forces in youth players complicates the assessment of the real magnitude of heading.[2,12] Longitudinal observations of training sessions are rare despite the much larger rate of overall football exposure.[2] There is less knowledge about heading exposure in training over a longer period of time and various training cycles, although needed for a realistic evaluation of heading loads.

The gold standard for analyzing head injury mechanisms in football is video observation,[13–15] which more and more frequently is used to assess heading exposure.[16–18] Recently published studies investigated heading frequencies and types by the use of video observation in a large-scale cross-sectional design across eight European countries[16] or by direct observation in an international youth football tournament.[19]

The aim of this prospective longitudinal study was to describe heading exposure and characteristics in elite children's and youth football players after two seasons of video observation in both match and training. Therefore, we examined heading frequency and characteristics in elite German youth football of different age groups in match and training.

2 | MATERIALS AND METHODS

2.1 | Study population and design

In this prospective longitudinal cohort study, heading exposure and characteristics were investigated in a cohort of elite children's and youth football players over two seasons using standardized video analysis. Four regional youth teams of different age groups consisting of one male Under-11, Under-15, and Under-19 and one female Under-17 team with a high level of play were approached via personal contact to club officials and coaches. Inclusion criteria for participating teams were regular training and regular participation in official matches in one of the top three leagues of their age group. All players and their parents/guardians (if participants were under 18 years) provided written informed consent before participation. The study was approved by the ethics committee of the State Medical Board (Ärztekammer Westfalen-Lippe in Münster, Germany) (2019-321-f-S) and registered at DRKS (DRKS00018923).

All matches and training sessions of participating teams were videotaped during the seasons of 2019–2020 (August 2019–March 2020) and 2020–2021 (July–November 2020; March–September 2021). Teams were active in the three highest German junior leagues (Westfalen-, Regional-, Bundesliga). All league, cup, friendly matches, and tournaments with regular football (no futsal) rules were involved in match play analyses. Training included match warm-ups except for individual training sessions during the COVID-19 pandemic, during which no headers were performed.

2.2 | Patient and public involvement

The study design and conduct were discussed with club officials before starting with video observation. Data analysis, writing, or editing was done without public involvement.

2.3 | Video analysis

Standardized heading protocols were used for assessing headers in all players equally, with previously defined criteria.[20] In player-based analyses of headers, the following characteristics were evaluated from video recordings by team-related analysts, and collected using a common Research Electronic Data Capture (REDCap) tool hosted at Paderborn University[21]:

- Header type: without heading duel, heading duel; if duel: without contact to another player, contact to teammate or opponent.
- Match situation: free game play (high pass ball, flank, kick, header), corner kick, throw-in, free-kick/goal-kick.
- Player position: goalkeeper, defender, midfielder, striker.
- Flight course of the ball: <5 m, 5–20 m, 20–50 m, >50 m.
- Contact to player's head: frontal, parietal, occipital, temporal, facial.

The flight course of the ball could not precisely be measured, but auxiliary quantities such as size, boundaries, and areas of the field were used for interpretation and classification. Calculation of individual match and training exposure was defined by *number of matches or training sessions x duration of match or training session in hours*.[22] In the case of head injuries, the injury mechanism was analyzed using a standardized injury registration form, orientated on previous studies.[23]

2.4 | Inter-rater reliability

Raters were trained in video analysis by discussing (especially unclear) heading situations utilizing the standardized protocol and practice analyses before the study started. Five randomly chosen matches and eight training sessions from male Under-11 (one training), Under-15 (three trainings, one match), Under-19 (two trainings, two matches), and female Under-17 teams (two trainings, two matches) were screened by three independent video analysts. Concordance of results on total headers was assessed by calculating intra-class correlation coefficients (ICC; one-way random).

2.5 | Statistics

Statistical analysis was performed using Microsoft Excel 2019 and SPSS 27 (IBM Statistics, New York, USA). Median, minimum, and maximum number of headers per match/training session were calculated and individual heading exposure was derived from headers per player per match hour/training session. Similar to previous literature, incidence rates (IR) per 1000 match/training hours with 95% confidence intervals (CI) were calculated.[16]

IR was compared between age groups by incidence rate ratios (IRR). Additionally, IR was checked for normal distribution by Shapiro–Wilk test. To detect group differences in match play and training, Kruskal–Wallis test was used due to not normally distributed data. Wilcoxon test was used for comparing match and training IR within age groups. Correction for multiple comparison was done using false discovery rate.

3 | RESULTS

3.1 | Demographics

The average observation period for all 134 included youth players was 11 (±5) months. Two players were only exposed to training, not matches. Mean age of Under-11, Under-15, Under-19 males, and Under-17 females was 9.7 (±0.5), 13.8 (±0.4), 17.4 (±0.5), and 14.9 (±0.8) years, respectively. ICC for inter-rater reliability of heading frequency was 0.998 (95% CI 0.995–0.999).

3.2 | Heading exposure and incidence

In total, 275 matches and 673 training sessions were recorded, corresponding to a total match, and training exposure of 13 506.5 h. A total of 22 921 headers in match play and training were registered and examined. Exposure time, number of recorded matches and training sessions, total headers, and average heading IR per player per age group are shown in Table 1.

3.2.1 | Match play

Heading differences between age groups in match and training are visualized in Table 2 as IRR and Figure 1. Heading incidence in Under-11 males was lower compared to Under-15 and Under-19 males (by −22%, −36%, respectively). Under-17 females had lower incidences compared to Under-11 (−16%), Under-15 (−35%), and Under-19 males (−47%). The difference between Under-19 and Under-11 males ($z = -2.732$, $p = 0.018$), as well as Under-19 and Under-17 females ($z = 3.762$, $p < 0.01$) showed significant post hoc results. 85% of all players headed zero or one to two times per match hour. No player was heading more than four times per match hour on average in all groups.

3.2.2 | Training sessions

IR in training between age groups differed significantly (χ^2 (3) $= 32.73$, $p < 0.001$). Under-11 males had significantly lower incidences compared to all older age groups (by more than −48%, $p < 0.01$). There were no further significant group differences. Average distributions of heading numbers per training session per player are shown in Figure 2. Heading IR differed significantly between training and match in all age groups ($p < 0.04$).

3.3 | Heading characteristics

3.3.1 | Match play

Proportions of heading characteristics across age groups are displayed in Table 3. In match play, most frequently single intentional headers without heading duels were registered (58%). In 58% of all heading duels, there was contact with an opponent. In 39% of all duels, there was no contact

TABLE 1 Number of recorded matches/training sessions, game format, exposure time, total headers, headers per player per match hour/training (mean ± SD), and heading IR (per 1000 match/training hours) per player.

	Under-11 males	Under-15 males	Under-17 females	Under-19 males	Total Cohort
Players (*n*)	28	27	39	38	132
Matches (*n*)	80	71	54	70	275
n Players per match per team, median (min–max)	7 (3–7)	11 (5–11)	11 (9–11)	11 (5–11)	11 (3–11)
Minutes per match, median (min–max)	20 (10–75)	70 (10–80)	80 (30–90)	90 (15–90)	70 (10–90)
Match exposure (h)	278	522	789	877	2466
Total headers (n)	316	942	925	1846	4029
Headers per match	4.0	13.3	17.1	26.4	14.7
Median	3	9	17	27	11
Range (min–max)	0–16	0–51	0–47	0–59	0–59
Headers per player per match hour	1.3 ± 0.9	1.6 ± 1.1	1.1 ± 0.8	1.9 ± 1.0	1.5 ± 1.0
Heading IR per player	1256	1608	1050	1927	1460
95% CI	884–1627	1195–2022	802–1298	1595–2259	1289–1632
Players (n)	29	28	39	38	134
Training sessions (n)	110	182	134	247	673
Training exposure (h)	1618	2812	2264	4346	11 041
Total headers (n)	1222	6419	4105	7146	18 892
Headers per training	11.1	35.3	30.6	28.9	28.1
Median	4	10	3	11	7
Range (min–max)	0–144	0–620	0–902	0–236	0–902
Headers per player per training	1.1 ± 0.6	2.7 ± 1.8	2 ± 1.1	1.9 ± 0.8	1.9 ± 1.3
Heading IR per player	718	2151	1662	1419	1492
95% CI	564–873	1592–2710	1381–1942	1190–1648	1316–1669

Note: Size 4 balls were used in Under-11 males, while Under-15 males, Under-17 females, and Under-19 males used size 5 balls.
Abbreviations: CI, confidence interval; h, hours; IR, incidence rate.

with another player, followed by contact with many players (2%) and a teammate (1%). The predominant match situation for headers was free game play (54%). In 54% of all headers, the flight distance of the ball before heading was between 5 and 20 m with varying proportions in age groups. The number of headers flying >20 m was very low in Under-11 males (11%) and increased with increasing age. The contact point to the player's head predominantly was at the frontal part (79%), while in Under-11 headers were also played with other parts. In all age groups, the smallest proportion of headers was performed by goalkeepers (<6%), whereas midfielders accounted for 43% of all headers, followed by defenders (34%).

3.3.2 | Training sessions

In training, most of all headers were played without duels in all age groups (91%, 7% with duel, 2% no info). In heading duels, 48% of headers were without body contact to another player. The predominant situation was free game play (84%). The flight distance was <5 m in 65% of all headers, followed by 29% between 5 and 20 m, 6% between 20 and 50 m and less than 1% >50 m. The ball most frequently hit the frontal part of the head (93%), followed by the parietal part (4%). Heading characteristics in different age groups are presented in Table S1.

3.4 | Head injuries

Three concussions were registered in match play, with participation of opponents. Two injuries occurred in free game play while changing direction (Under-19 male) and being shot from nearest distance (Under-17 female). An aerial heading duel caused one further concussion (Under-19 male). No head injuries occurred during training sessions.

TABLE 2 Heading difference between age groups as incidence rate ratio in match play (MP) and training sessions (TS).

	Under-11 male	Under-15 male	Under-17 female	Under-19 male
Under-11 male				
MP	–	0.78 (0.55–0.91)	1.20 (0.83–1.5)	0.64 (0.42–1)*
TS		0.33 (0.26–0.4)*	0.44 (0.31–0.55)*	0.52 (0.39–0.63)*
Under-15 male				
MP	1.28 (0.93–1.62)	–	1.53 (0.88–1.82)	0.82 (0.69–1.07)
TS	2.99 (2.37–3.62)*		1.33 (0.98–1.61)	1.55 (1.18–1.91)
Under-17 female				
MP	0.84 (0.56–1.03)	0.65 (0.44–0.76)	–	0.53 (0.39–0.68)*
TS	2.25 (1.67–2.96)*	0.75 (0.58–0.96)		1.17 (0.92–1.42)
Under-19 male				
MP	1.57 (1.04–1.85)*	1.22 (0.85–1.29)	1.87 (1.27–2.22)*	–
TS	1.92 (1.51–2.41)*	0.64 (0.49–0.8)	0.85 (0.67–1.04)	

Note: 95% confidence intervals in parentheses. Kruskal–Wallis test, false discovery rate correction, *$p < 0.05$.

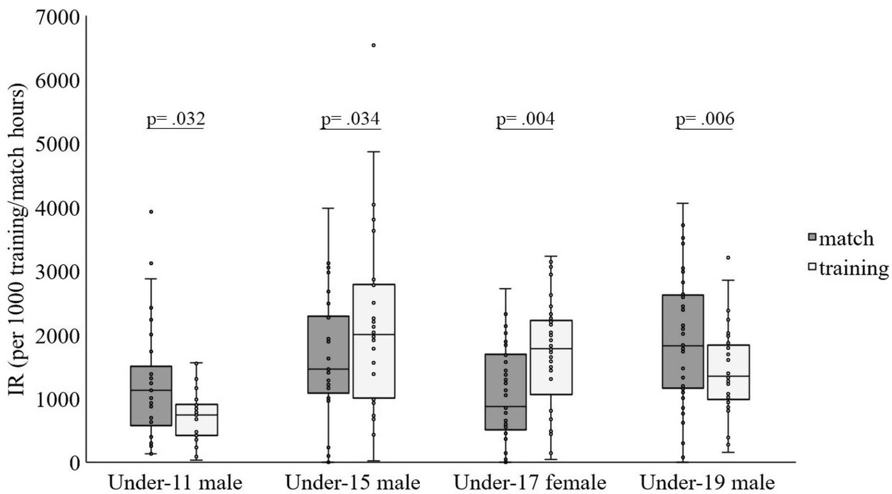

FIGURE 1 Mean heading incidence in match play and training sessions, Wilcoxon test.

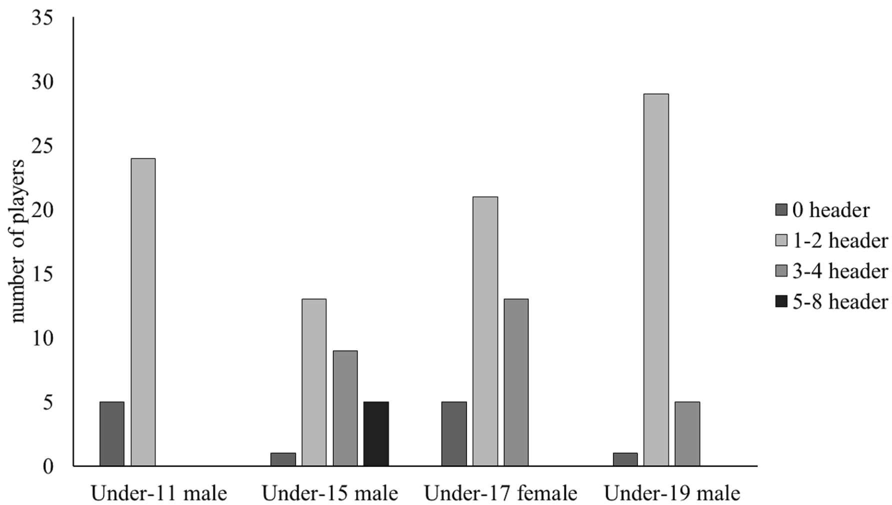

FIGURE 2 Number of players with number of headers per training session.

4 | DISCUSSION

To the best of our knowledge, this is the first study investigating heading exposure and characteristics in a large cohort of German elite children and youth football players in a longitudinal design across two seasons based on complete video observation of all matches and training sessions. With excellent inter-rater reliability during video

TABLE 3 Percentage distribution of match situation, heading duel, flight distance, point of contact to the player's head, and position in match play per age group.

	Under-11 males	Under-15 males	Under-17 females	Under-19 males
Situation (%)				
Free game play	44	57	45	67
Free kick	1	8	2	6
Goal kick	14	10	19	8
Throw-in	22	22	30	15
Corner kick	13	4	4	4
No info	5	0	0	0
Heading duel (%)				
Without duel	64	64	58	49
With duel	31	36	42	51
No info	5	0	0	0
Flight distance (%)				
<5 m	11	12	14	12
5–20 m	73	53	56	39
20–50 m	11	33	28	39
>50 m	0	2	2	10
No info	6	0	0	0
Contact to players head (%)				
Frontal	62	72	86	91
Temporal	10	6	1	1
Parietal	17	19	10	7
Occipital	1	2	1	1
Facial	6	2	2	1
No info	5	0	0	0
Position (%)				
Goalkeeper	8	0	0	3
Defender	25	37	38	35
Midfielder	37	47	47	42
Striker forward	25	14	15	21
No info	5	2	0	0

analysis, it became evident that in match play individual heading incidences were lowest in Under-11 players and increased with increasing age in males. In training sessions, constituting the highest amount of football and heading exposure, heading was a rare phenomenon in Under-11 males, showing significantly lower incidences compared to older age groups. Also, heading exposure differed individually.

4.1 | Heading exposure in youth football

Total heading frequency per match and IR in matches increased with increasing age (in males). This finding confirms previous studies[19,24] and cross-sectional observations in eight European countries.[16] However, total heading numbers and IR in match play were lower and revealed larger 95% CIs in our study, compared to observations from Beaudouin et al. (IR Under-10: 1677, Under-12: 2078, Under-16 males: 2665, Under-16 females: 1454).[16] Additionally, the results of the present study showed high percentages of players heading zero or one to two times per match hour on average and no player heading more than four times in all age groups, which is in line with previous reports that quantified heading exposure during an international youth football tournament, including Under-12 to Under-20 players from both sexes.[19]

There were also many players with one to two headers or less per training session in Under-11 and Under-19 males. However, in Under-15 males, less than half of the players were heading 0–2 times and five players performed five to eight headers per training session, accounting for 34% of all headers in that age. This substantial variation in individual heading numbers between youth players was already described in match play[19] and might be reasoned by training specific to players' requirements and demands, as position showed to affect heading exposure.[25] Heading incidence in training of Under-15 males is comparable to rates in the literature (IR: 2511).[16] The number of headers per player per training in Under-11 males, Under-19 males, and Under-17 females is similar to that of other observational studies with Under-13 males, 19-year-old males (1 header per player per training), and Under-16 females (approximately 1.4 headers per player per training).[26–28] However, incidences in Under-11 are much lower in the present study, compared to the Under-12 in Beaudouin et al. (IR: 5007).[16] One reason could be a higher awareness on limiting the heading burden under preventative aspects in younger age groups at present due to media attention, previous limitations of heading in US soccer[29] and recommendations by 2020 published UEFA heading guidelines.[30] Also, our data might represent more realistic heading exposures, compared to cross-sectional studies with an assessment of only one training session per team. Unfortunately, studies examining heading exposure in training are rare so far, despite the proportion of training sessions being much larger compared to matches.[2,26,27] The (rapid) increase in IR from Under-11 to Under-15, specifically in training might partly be explained by an increase in field size in these age groups as the number of players per team in matches increased and differing training plans. As lower heading numbers are associated with small-sided games, the field size is an influencing factor for technical demands.[31,32]

In all age groups heading IR differed significantly between training and match. In Under-15 males and Under-17 females, heading incidence in training exceeded match play by around 600 headers per 1000 player hours. Additionally, the upper range of headers per training was much higher compared to match for all ages. Different to matches, training sessions offer many opportunities for controlling (individual) heading behavior, as content and organization largely depend on trainer's intentions. Taken together with previous reports,[16] these results may provide the basis for strategies for training headers in youth players and underline the importance of systematic heading observation in training.

4.2 | Heading characteristics

Contact with another player, especially head-to-head contact like in heading duels is the primary mechanism of head injuries in adult football players.[13,33] In all groups, most headers were performed without heading duels. Duels were without contact to another player even in more than one-third of all headers in youths and therefore at low risk for head injuries.

Although ball-to-head contact is rarely associated with head injuries, ball velocity and contact force between ball and player's head in heading is an important risk factor regarding potential head injury consequences.[33,34] In training sessions, headers were most frequently performed from <5 m flight distance. These short-distance headers are presumably performed at lower velocities and with lower forces to the head than long-distance headers.[12,19] In matches, the number of long-distance headers flying >20 m was very low in Under-11 males and slightly increased with increasing age, matching results from Sandmo et al.,[19] most likely as a result of the increasing field size and muscle strength in players.

Head impact location most frequently was at the frontal part, usually representing intentional headers.[1,34] In the youngest age group, we found nearly one-third of all impacts at the temporal, parietal, and occipital part, which is in line with results from Harris et al.[35] These head impact locations could represent improper techniques leading to larger rotational velocities and higher linear accelerations of the head.[36]

4.3 | Methodological consideration

Variabilities in heading frequency and different training practices between countries because of differences in training curricula and rules in match play[16] may have influenced the results. Also, contents of training and way of playing might depend on the clubs and coaches' interests and preferences. All teams were active on a very high level, but heading exposure in other leagues or teams might differ. Nevertheless, the longitudinal design across two seasons of observation with a sample covering a large age span is strengthening the validity of results.

Unfortunately, only one female Under-17 team meeting the inclusion criteria was regional available and included in this study. For assessing heading exposure in females of different age groups, further research is needed.

Despite canceled training sessions and matches due to pandemic situations, the number and exposure time of observed training sessions is much higher compared to previous studies.[16,26,27,37] Single training sessions showed at times very high heading exposures, due to sessions focusing on heading training. Although the coaches were advised to execute "normal" training during study participation, video observation might have motivated some players and/or coaches to give either more or less attention to heading. Over the course of the study, however, those effects have most likely weaned off.

Many previous studies used questionnaires and interviews to assess heading exposure.[4,8,38] Although positive correlations between self-reported and observed heading exposures were found,[39] youth players systematically overestimated the actual header number in a recent study.[37] Player observation is needed to accurately quantify heading frequency in youth soccer.[18] Therefore, the method of video analysis is a study strength, allowing exact analysis of heading characteristics. Unfortunately, biomechanical parameters like forces to the head were not captured.

5 | PERSPECTIVE

Under-11 football players showed low heading incidences, which increased with increasing age in matches, whereas Under-15 males showed high heading exposure in training. Due to variations in heading exposure between age groups strategies for training headers in youth players should account for age-related differences. Head impact location in Under-11 might represent improper techniques in one-third of all headers in matches. A reduction of headers, for example, by more small-sided games, might decrease the use of improper heading techniques.[2]

As predominantly five Under-15 males showed high heading exposures in training, special attention to individual heading burden in training is needed. Education and sensitization of coaches are important to reduce heading drills to what is deemed necessary for learning correct heading techniques and to increase awareness for players with a high preference for heading. Additionally, training offers many opportunities to control for heading frequency, recovery times, flight distance, or weight of the ball. Training sessions and individual heading behavior should specifically be addressed when heading burden and regulations are addressed.

This study provides a basis for future studies that investigate the relationship between realistic heading exposures and potential (long-term) effects as heading exposure and characteristics are well described.

AUTHOR CONTRIBUTIONS

RR and CR were responsible for the conception and design of the study. WK conceptualized the heading protocol. RR was responsible for data collection over the study period. RR, FH, and LD conducted the statistical analyses. RR wrote the paper. The draft of the paper was critically revised by LD, FH, WK, and CR.

ACKNOWLEDGMENTS

The authors wish to thank the study assistants Romina Müller, Leonie Schmidt, Jonas Schröder, Darius Krösche, Theresa Koch, Hannes Niemann, and Alexander Böhnhardt for their support during data collection and video analysis. They would also like to thank the football clubs SC Paderborn, and Delbrücker SC, specifically Thorsten Koch and Hubertus Austerschmidt, as well as the teams and players for study participation. Many thanks also to Christian Gölz and Roman Gaidai for preparation and administration of REDCap database. Open Access funding enabled and organized by Projekt DEAL.

FUNDING INFORMATION

This study was funded by the German Federal Institute of Sports Science.

CONFLICT OF INTEREST STATEMENT

CR receives scientific funding for projects on traumatic brain injuries and heading from the Federal Institute of Sports Sciences (Germany) and the Heinz Nixdorf Westfalian Foundation. He is a member of the medical committee of the German Football association (DFB) and provides counseling on the management of traumatic brain injury to the Union of European Football Associations (UEFA).

DATA AVAILABILITY STATEMENT

Datasets are not available due to confidentiality of players and teams.

PATIENT CONSENT STATEMENT

Written and verbal consent was obtained directly from all participants, and parents or guardians, if the participant was under the age of 18.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Reeschke R, Haase FK, Dautzenberg L, Krutsch W, Reinsberger C. Training matters: Heading incidence and characteristics in children's and youth football (soccer) players. *Scand J Med Sci Sports*. 2023;33:1821-1830. doi:10.1111/sms.14408

SUPPLEMENTAL MATERIALS

Table 1 Percentage distribution of heading duel, flight distance, and point of contact to the players' head in training per age group

	Under-11 males	**Under-15 males**	**Under-17 females**	**Under-19 males**
Situation (%)				
Free game play	51.4	84.7	96.5	95.9
Free kick/goal kick	1.4	0.6	1.1	1.6
Throw-in	9.8	0.4	2.8	0.9
Corner kick	3.4	0.4	0.3	1.3
No info	34	14	0	0.3
Heading duel (%)				
Without duel	87	90	98	89
With duel	13	3	2	11
No info	0	7	0	0
Flight distance (%)				
< 5 meter	70	54	81	55
5-20 meter	29	42	17	30
20-50 meter	1	5	2	14
> 50 meter	0	0	0	1
No info	0	0	0	0
Contact to players head (%)				
Frontal	88	89	97	95
Temporal	3	2	0	1
Parietal	7	6	1	3
Occipital	1	2	0	1
Facial	1	1	2	1
No info	0	0	0	0

ACCEPTED: April 2024
PUBLISHED ONLINE: May 2024
Reeschke R, Dautzenberg L, Koch T, Reinsberger C. Neurocognitive performance, vestibulo-ocular function and postural control in youth male soccer and basketball players of different ages. Dtsch Z Sportmed. 2024; 75: 90-96. doi:10.5960/dzsm.2024.597

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Neurocognitive Performance, Vestibulo-Ocular Function and Postural Control in Youth Male Soccer and Basketball Players of Different Ages

Neurokognitive Leistung, vestibulo-okuläre Funktion und posturale Kontrolle jugendlicher männlicher Fußball- und Basketballspieler verschiedener Altersklassen

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Summary

- **Purpose:** Neurocognitive, vestibulo-ocular, and balance assessments can assist in screening and management of potential sports-related concussions. This cross-sectional study aimed to examine the effect of age on neurocognitive performance, vestibulo-ocular function, dynamic visual acuity, and postural control in high-level adolescent ball sport athletes.
- **Methods:** In 139 male adolescent soccer and basketball players (under-11, under-15, under-19) assessments of neurocognitive performance (CNS Vital Signs), vestibulo-ocular reflex (video head impulse test), dynamic visual acuity (dynamic visual acuity test), and postural control (stability evaluation test) were performed. ANOVA and Kruskal-Wallis tests (post-hoc Bonferroni correction) were used for comparisons between age groups.
- **Results:** Neurocognitive functioning (composite memory, psychomotor speed, reaction time, complex attention, cognitive flexibility, processing speed; $p<0.008$, $\eta^2=0.24$ to 0.71), vestibulo-ocular reflex gain ($p=0.018$, $\eta^2=0.06$), dynamic visual acuity loss ($p<0.001$, $\eta^2=0.11$), and sway velocity ($p<0.001$, $\eta^2=0.36$) differed significantly between age groups. Medium to large effects, with better performance in older compared to under-11 males, were found.
- **Conclusion:** Under-11 male athletes revealed considerably lower neurocognitive, vestibulo-ocular reflex, dynamic visual acuity, and postural control performance compared to older youth athletes. Hence, this age group should be tested in smaller intervals to assess age-adequate performance and post-injury impairment. Further longitudinal studies may aid in the development of normative vestibulo-ocular reflex gain, dynamic visual acuity, and sway velocity values for ball sports.

KEY WORDS:
Baseline, Neuropsychological Test, Visual Acuity, Vestibular System

Introduction

Sports-related concussions (SRC; the mildest form of mild traumatic brain injury (mTBI)) most frequently occur in contact and collision sports and result in a range of clinical signs and symptoms (23). A multimodal assessment is recommended in the diagnosis and management of SRC, including investigations of neurocognition, vestibulo-ocular reflex (VOR), oculomotor function, and balance (5, 23). Objective tools such as the standardized computerized neurocognitive exam tools, video head impulse test (vHIT), assessment of dynamic visual acuity (DVA), and postural sway via force plate are already used in the clinic and research on mTBI (3, 11, 18). Individual pre-injury baseline data or an adequate norm sample greatly facilitate the interpretation of data obtained after SRC. While using norm values seems to have a high specificity regarding cognitive impairments and is sometimes more feasible, baseline data are considered to be more sensitive in neurocognitive testing (4, 17).

In ball sports such as soccer and basketball, a large proportion of players are adolescents (6), a period in which the brain, particularly executive functions, and body develop (13). Neurocognitive performance has been shown to develop noticeably each year in high-school athletes between the ages of about 14 to 18, whereas younger ages have not been examined (27). While there seems to be no difference between age groups in the VOR of young soccer players (30), single studies found age-related changes in DVA (16). Postural stability was found to improve with age in youth (28), while balance did not depend on age in adolescent and adult soccer players (30). Studies investigating vestibular function in youth athletes are rare (22, 30). Therefore, the influences of age on performance in computerized neurocognitive, vestibulo-ocular, and postural control assessments in adolescent athletes, particularly of young age, remain to be elucidated, to identify optimal intervals to repeat baseline examinations. Also, age-appropriate norm values for youth ball sport players need to be investigated.

This cross-sectional study aimed to examine the effect of age on neurocognitive performance, VOR, DVA, and postural control in high-level adolescent ball sport players. We hypothesized to find signifi-

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Table 1

Description of test battery to assess neurocognitive, vestibulo-ocular, and postural control performance with parameters used for analysis. DVA=dynamic visual acuity; VOR=vestibulo-ocular reflex.

TEST	DESCRIPTION OF ASSESSMENT	PARAMETER
CNS Vital Signs	To assess neurocognitive performance, 7 established neuropsychological tests (Verbal Memory, Visual Memory, Finger Tapping, Symbol Digit Coding, Stroop Test, Shifting Attention, and Continuous Performance) were performed in the athlete's native language from which 11 domain scores were generated and 6 used for analyses.	Domain scores: composite memory, psychomotor speed, reaction time, complex attention, cognitive flexibility, processing speed
Video head impulse test	VOR in all six semicircular canals was investigated while the participant wore monocular goggles with an infrared camera recording the right eye. The height of the fixation dot on the wall was 120 cm, with 1-meter distance between the participant and the wall. The athlete's head was rapidly and unpredictably turned at changing directions with amplitudes of 10-20 deg and at peak head velocities between 120-250 (lateral) and 100-250 (vertical) deg/s. A minimum of 20 (lateral) and 10 (vertical) correct impulses to each direction, with minimum frame rates of 220 frames/s, were needed for test completion.	Total, lateral, anterior, and posterior VOR-gain (eye movement velocity / head movement velocity)
Dynamic visual acuity test	After the assessment of static visual acuity and perception time, lateral DVA was measured. Perception time should be <60 ms to guarantee valid results. Head movement velocity should be between 85-120 deg/s with an amplitude of around 20 deg in each direction. The distance between display and participant was three meters.	Lateral loss between static and dynamic visual acuity (DVA loss; in logMAR)
Stability evaluation test	Balance performance was measured in three different stances on a static force plate: double-leg, single-leg, and tandem stance, each on a firm and foam surface. The participant was asked to stand as motionless as possible, with eyes closed and hands in hips for 20 seconds in each condition.	Sway velocity (in deg/s) of all six stances

Table 2

Characteristics of ball sport athletes with mean age, height, body mass index, career length in sports, migraine, and concussion prevalence. BMI=body mass index.

	UNDER-11 MALE	UNDER-15 MALE	UNDER-19 MALE	TOTAL
n (% soccer)	45 (64.4)	43 (67.4)	51 (74.5)	139 (69.1)
Age, years (SD)	10.4 (0.6)	14.5 (0.6)	17.8 (0.7)	14.4 (3.1)
Height, cm (SD)	145.3 (8.8)	176.6 (11.5)	184.7 (9.4)	169.7 (19.7)
BMI (SD)	16.7 (1.5)	19.6 (1.7)	22.4 (1.3)	19.8 (2.8)
Career length, years (SD)	5.0 (1.8)	7.9 (2.1)	11.3 (2.8)	8.3 (3.5)
Education, n (%)				
primary school	13 (28.9)	0 (0)	0 (0)	13 (9.4)
high school	32 (71.1)	42 (97.7)	30 (58.8)	104 (74.8)
graduated	0 (0)	0 (0)	15 (29.4)	15 (10.8)
no information	0 (0)	1 (2.3)	6 (11.8)	7 (5.0)
Migraine, n (%)	1 (2.2)	1 (2.3)	6 (11.8)	8 (5.8)
12-month concussion prevalence, n (%)	0 (0)	2 (4.7)	2 (3.9)	4 (2.9)
Lifetime concussion prevalence, n (%)	2 (4.4)	6 (14.0)	14 (27.5)	22 (15.8)

cantly better neurocognitive, VOR, DVA, and balance performance with increasing age. Performance assessed by standardized computerized testing, vHIT, DVA test, and stability evaluation test (SET) were investigated regarding sports-specific differences within a pilot study, as baseline values may depend on sports-specific risk profiles aside from concussion (e.g. heading in soccer).

Methods

At the beginning of the seasons 2019/20 and 2020/21, players from high-level male under-11 (U11), under-15 (U15), and under-19 (U19) youth soccer and basketball teams were evaluated for neurocognitive, VOR, and postural control parameters. All players were approached via personal contact with club officials and coaches. Every athlete and their guardian (if <18 years) provided written informed consent before participation. The study was approved by the ethics committee of the Ärztekammer Westfalen-Lippe in Münster, Germany (2019-321-f-S) and registered at DRKS (DRKS00018923).

The inclusion criteria were regularly participating in official matches in one of the top three leagues of their age group and completion of minimum one test presented below. Exclusion criteria were head injuries, lower extremity injuries for testing postural control, or medication intake influencing the visual or vestibular system at the day of testing.

The study protocol included a collection of demographics, information on sports, medical, and head injury history via questionnaire, in addition to pre-season baseline tests (table 1). Neurocognitive performance was evaluated through a computerized assessment using CNS Vital Signs (Morrisville, NC, USA) (10). Six domain scores were used for analysis (24). Invalid scores were excluded based on the validity indicator (9). The VOR was quantified via vHIT (ICS Impulse, Otometrics, Taastrup, Denmark) (19). The VOR-gain of all semicircular canals was analyzed. Values of <0.8 (lateral), <0.6 (vertical), and ›

Table 3

Neurocognitive domain, VOR-gain, DVA Loss, and sway velocity scores for athletes of different age groups. SD=standard deviation; [a]=lower scores indicate better performance; VOR=vestibulo-ocular reflex; Effect sizes η^2 of 0.01, 0.06, and 0.14 correspond to small, medium, and large effects, respectively (2). **=p value <=0.001; *=Bonferroni corrected p value <0.017 in VOR-gain.

	UNDER-11 (N=45)		UNDER-15 (N=43)		UNDER-19 (N=51)		η^2
	MEAN	SD	MEAN	SD	MEAN	SD	
Neurocognitive function (n=139)							
Composite memory	93.90	8.50	99.90	7.40	98.80	6.10	0.113**
Psychomotor speed	137.50	17.00	177.70	24.10	192.80	21.70	0.586**
Reaction time[a]	838.70	92.50	649.30	96.20	608.00	72.10	0.574**
Complex attention[a]	23.00	10.90	17.50	13.10	11.30	6.30	0.256**
Cognitive flexibility	19.70	12.60	34.00	15.60	44.30	11.00	0.415**
Processing speed	35.80	7.80	53.00	11.30	59.00	10.60	0.429**
Executive function	22.90	11.50	36.80	15.20	46.50	10.80	
Simple attention	35.80	4.90	38.60	2.00	39.00	1.20	
Motor speed	100.00	14.30	122.40	18.40	132.50	15.80	
VOR-gain (n=136)							
Total	0.93	0.07	0.97	0.06	0.95	0.06	0.058*
Lateral							0.011
left	0.95	0.09	0.97	0.09	0.95	0.06	
right	1	0.07	1.02	0.07	1.02	0.06	
Anterior							0.025
left	0.84	0.13	0.9	0.09	0.89	0.08	
right	0.9	0.15	0.98	0.1	0.97	0.11	
Posterior							0.078*
left	0.91	0.12	0.97	0.1	0.94	0.11	
right	0.9	0.12	0.96	0.1	0.91	0.08	
DVA Loss (n=136)							
Lateral	0.22	0.08	0.17	0.09	0.16	0.08	0.110**
left	0.22	0.09	0.16	0.1	0.17	0.1	
right	0.22	0.11	0.17	0.11	0.15	0.09	
Sway velocity (n=139)							
Total	3.42	0.81	2.37	0.63	2.25	0.53	0.358**
double firm	0.98	0.26	0.72	0.18	0.69	0.2	0.252**
single firm	3.1	1.07	2.12	0.69	1.91	0.61	0.275**
tandem firm	2.54	1.18	1.73	1.04	1.4	0.6	0.297**
double foam	2.52	0.63	2.22	0.54	2.04	0.44	0.107**
single foam	5.66	1.83	3.72	1.1	3.7	1.15	0.287**
tandem foam	5.71	2.25	3.71	1.62	3.74	1.54	0.158**

>1.2 were counted as invalid (8). The DVA test (NeuroCom InVision, Natus Medical Incorporated, Seattle, USA) was implemented to measure DVA loss. Postural control was assessed via SET (NeuroCom VSR, Natus Medical Incorporated, Seattle, USA) to analyze sway velocity. Tests were carried out in successive stations.

Sample size calculation was based on an a priori power analysis (G*Power, v.3.1.9.4) using literature, which showed neurocognitive performance differences between 10 to 18-year-old athletes, for example in reaction time (η^2=0.22) (7). A minimum of 38 athletes in total were required to reach statistical power of 80% (η=0.05) for investigating age group differences. Statistical analysis was performed using SPSS 29 (IBM). Descriptive statistics are presented as the mean with standard deviation (SD) and frequencies with percentages. Parameters were checked for normal distribution by the Shapiro-Wilk test. To exclude effects of sports, comparisons in test scores between soccer and basketball players of the same age using t test or Mann-Whitney-U test and logistic regression models, adjusting for potential effects of career length, concussion history, migraine, and height, were conducted. ANOVA or Kruskal-Wallis test was used to compare parameters between age groups. If homogeneity of variance, tested using Levene's test, was violated in normally distributed data WELCH-ANOVA with Games-Howell post hoc analysis was used. Otherwise, post hoc tests with Bonferroni correction for multiple comparisons were conducted. The level of significance for statistical tests was defined as $p<0.05$ (Bonferroni corrected in neurocognitive domains: $p=0.008$). Effect sizes were expressed as eta-square with 0.01, 0.06, and 0.14 and Cohen's d with 0.2, 0.5, and 0.8 corresponding to small, medium, and large effects, respectively (2).

Results

In total, 139 athletes were enrolled in the study (table 2). No participant reported diagnosed ADHD, learning/mental disorders, or medication intake leading to exclusion.

There were no significant differences between soccer and basketball players of the same age in neurocognitive functions (composite memory: d=0.03 to 0.18; other domains: η^2=0.00 to 0.04), VOR-gain (d=0.11 to 0.63), DVA loss (d=0.01 to 0.52), and sway velocity (all p>0.05, η^2=0.00 to 0.06), also after adjusting for effects of confounders (see supplementary tables 4 and 5 online).

Age group differences and scores of neurocognitive domains, VOR-gain, DVA loss, and sway velocity for all ages are presented in table 3. Neurocognitive functioning differed significantly between age groups, showing large effects. Composite memory (U11 vs. U15: p<0.001, U11 vs. U19: p=0.005, d=0.67 to 0.75), psychomotor speed, reaction time, cognitive flexibility, and processing speed were significantly worse in U11 than in all older ages (p<0.001, η^2=0.24 to 0.71). Complex attention was worse in U11 compared to U19 (p=0.000, η^2=0.39). Cognitive flexibility differed significantly between U15 and U19 players (p=0.003, η^2=0.14).

The total VOR-gain differed significantly between teams (F (2, 133)=4.125, p=0.018), with lower scores in U11 than in U15 players (p=0.015, d=0.58). Considering the semicircular canals, the same medium effect was significant only for the average posterior gain (F (2, 134)=5.662, p=0.004, d=0.64).

Lateral DVA loss was significantly different between age groups (F (2,133)=8.204, p<0.001, η^2=0.11). U11 males showed significantly higher means than U15 (p=0.004, d=0.68) and U19 (p<0.001, d=0.8) males.

Total sway velocity differed between age groups (Chi^2 (2)=50.699, p<0.001, η^2=0.36). U11 did show significantly higher values than U15 and U19 males (p=0.000, η^2=0.36 to 0.46). These differences were observed for all stances, with large effects (p<0.001, η^2=0.16 to 0.38). No further differences were displayed.

Discussion

In this cross-sectional study, effects of age on neurocognitive performance, VOR, DVA, and postural control were investigated in high-level adolescent soccer and basketball players. Neurocognitive functioning, VOR-gain, DVA loss, and sway velocity differed significantly between youth age groups, with boys U11 revealing lower performance compared to older players. Scores of neurocognitive domains, VOR-gain, DVA loss, and sway velocity are presented as a step towards developing norm values for youth athletes of different ages playing soccer and basketball.

Neuropsychological, vestibulo-ocular, and balance assessments can assist in SRC screening and management (5). As these functions develop with age in adolescents, large intervals between baseline examinations may lead to inadequate performance representation and thus to difficulties in the interpretation of post-injury performance (13, 28). In all neurocognitive domains, significantly better performance with medium to large effects was observed in older compared to U11 male players in our study. These results confirm previous reports, where athletes aged 10 to 12 years performed worse than those aged 13 to 15 years, and 16 to 18 years on computerized neurocognitive testing (7). In another study, substantial improvement with age in 10-year-old adolescents over a two-year follow-up was found (1). Cross-sectional analyses of more than 3000 high school athletes demonstrated better neurocognitive performance each year of age in all domains except for verbal and visual memory (27). In the present study, moderate to large significant differences in cognitive flexibility and better performance in all domains but memory were found between U15 and U19 males, confirming previous findings.

The average VOR-gain was significantly higher in U15 than in U11 players. These results are partly in line with results from Tarnutzer et al., as they found main effects for age and lower VOR-gains in <18-year-old high-level athletes compared to older ages (30). Taking the semicircular canals into account, age-related differences were found only for the posterior semicircular canals in this study, supporting an impact of age described for the vertical semicircular canals in ice-hockey players (30). In high-level soccer players aged 13-39 years, no age-related changes were found in previous literature (30). This could be in contrast to our results, while the younger age of players in our study seems crucial. As no further differences between U19 and younger groups appeared, the findings extend the results of previous studies showing no age-dependency of VOR-gain in adolescents (20).

Lateral DVA loss was significantly better in U15 and U19 than in U11 players, with moderate to large effects. Similar to the presented results, Ishigaki et al. found a rapid development in DVA between the ages of 5 and 15 years in a fixed head and moving optotype testing situation (12). Further studies corroborated age-related effects on DVA (16), whereas no age group differences were found in other studies (16, 26). The DVA in adolescents has rarely been investigated in previous studies and the use of different testing paradigms complicates comparisons to our results. Therefore, the presented data add valuable information regarding the application of DVA baseline testing in adolescent ball sport athletes. Sports participation might also have influenced the results, as U19 players had a mean career duration of 11 years compared to 5 years in U11 (14).

A review on age-related differences in balance concluded considerable disagreement on the (non-)linearity of postural sway development in children (31). The present study revealed large age-related differences in sway velocity between U11 and older athletes, with better performance in older players. This confirms data presented in a review and meta-analysis by Schedler et al. (28). They found better balance performances in adolescents compared to children, indicating that maturation of postural control possibly is not completed in childhood, where sensory integration improves and postural control strategies change (28, 29). Increased muscle strength and better attentional capabilities by age might also justify age group differences (28). Another study on young athletes additionally showed that postural stability scores significantly improved between 9 and 13 years of age (22).

Between soccer and basketball players, no differences in pre-season testing were found, which is in line with the literature (7, 21, 25). Further ball sports should be included in future studies for better evidence regarding sports-specific effects.

For an adequate post-injury interpretation, the described developmental neurocognitive, vestibulo-ocular, and balance changes between ages 10 and 14 indicate the necessity for repeated baseline testing in this age range. Differences between 14 and 18-year-old ball sport players seem less significant, while optimal intervals for collecting baseline values in adolescence need to be further evaluated in future longitudinal studies. ›

Some methodological considerations need to be taken into account. The current study was a cross-sectional study. However, this approach is frequently used in literature (7, 30) and age groups were well comparable. Unfortunately, only male athletes were included, as female teams meeting the inclusion criteria with comparable age were not regionally available. To investigate influences of age, sex, and sports on neurocognitive domains, VOR, and postural control in female adolescent athletes, further research is needed. Four U19 players had already taken the test battery before study participation due to baseline or concussion assessment. In these individuals, influences of possible learning effects cannot be ruled out. The order of test administration within the assessment battery may influence performance across assessments (15). While the order of testing (e.g. CNS Vital Signs – DVA - SET – vHIT) was different between athletes, the proportional distribution of testing order was similar across groups, minimizing influences on results. While vHIT was applied by the same investigator, granting similar peak head velocities in all participants, neurocognitive, DVA, and postural control tests were conducted by different examiners. As CNS Vital Signs is a self-administered assessment, sway velocity was measured via force plate, and inter-rater reliability was previously described, no operator-dependent influences on test results are assumed (10, 26). In contrast to testing in the 2019/20 season, some athletes needed to wear masks during testing in 2020/21 season due to COVID-19-specific hygiene conditions. However, a standardized setting and operation procedure for the tests should have guaranteed valid, reliable measurements and should be adhered to in future studies. Cumulative overt catch-up saccades per trial, assessing VOR, were not analyzed, as they were shown to be below the cut-off for indicating peripheral-vestibular deficits in adolescent athletes (30).

Conclusions

U11 males revealed considerably lower neurocognitive, VOR, DVA, and postural control performance than older youth ball sport athletes. Individual reference values are needed for a sensitive detection of potential head injuries. When collecting baseline values, soccer and basketball players under the age of 11 should be tested in smaller intervals up to the age of 14, for age-adequate performance representations and post-injury interpretation. Analyses of exact time periods when changes might be most noticeable between ages 10 and 14 were not possible and optimal intervals for test administration need to be evaluated in future longitudinal studies. As a perspective, neurocognitive, VOR-gain, DVA loss, and sway velocity scores were presented as preliminary norm values for high-level male adolescent soccer and basketball athletes, while further studies are needed to replicate and extend particularly vestibulo-ocular, and balance scores. ■

Conflict of Interest

The authors have no conflict of interest.

Acknowledgements and Indications of Support and Cooperation

The authors wish to thank the study assistants Romina Müller, Leonie Schmidt, Jonas Schröder, Darius Krösche, Theresa Koch, Hannes Niemann and Alexander Böhnhardt for their support during data collection. They would also like to thank the soccer club SC Paderborn 07, and the basketball club Paderborn Baskets 91, as well as the teams and players for study participation. Many thanks also to Christian Gölz and Roman Gaidai for preparation and administration of REDCap database.

Funding

This study was funded by the German Federal Institute of Sports Science. All authors have completed the ICMJE Uniform Disclosure Form at www.icmje.org/coi_disclosure.pdf and declare: CR receives scientific funding for projects on traumatic brain injuries and heading from the Federal Institute of Sports Sciences (Germany) and the Heinz Nixdorf Westfalian Foundation. He is a member of the medical committee of the German Football association (DFB) and provides counseling on the management of traumatic brain injury to the Union of European Football Associations (UEFA).

Ethical Approval

This study is approved by the Ethics Committee of the Ärztekammer Westfalen-Lippe in Münster, Germany (2019-321-f-S). Written and verbal consent was obtained directly from all participants, and from parents or guardians, if the participant was under the age of 18.

Summary Box

Under-11 males revealed considerably lower neurocognitive, vestibulo-ocular reflex, dynamic visual acuity, and postural control performance than older youth ball sport athletes.

When collecting individual baseline values, soccer and basketball players under the age of 11 should be tested in smaller intervals up to the age of 14, for age-adequate performance representations and interpretations post potential head injuries.

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Table S4

Differences between soccer and basketball players of the same age presented as p-values. Note: The level of significance after Bonferroni correction was defined as $p<0.017$.

	UNDER-11	UNDER-15	UNDER-19
Composite memory	0.68	0.92	0.59
Psychomotor speed	0.74	0.87	0.89
Reaction time	0.79	0.33	0.59
Complex attention	0.95	0.88	0.66
Cognitive flexibility	0.25	0.69	0.75
Processing speed	0.92	0.68	0.15
VOR-gain	0.13	0.26	0.65
DVA loss	0.71	0.04	0.32
Sway velocity	0.92	0.31	0.10

Table S5

Association between playing soccer and shown variable using basketball players as a reference. Using binary logistic regression with sports (1=soccer, 0=basketball) as dependent variable, adjusted for career length, concussion history, migraine, and height (only for sway velocity) as predictors in block 1, before adding neurocognitive domain scores or vestibulo-ocular variables in block 2. Note: B=regression coefficient; CI=confidence interval; DVA=dynamic visual acuity; Exp(B)=odds ratio; SE=standard error; VOR=vestibulo-ocular reflex; *=$p<0.05$ & $p<0.008$ for neurocognitive scores (Bonferroni corrected). Difference Nagelkerkes R2 between block 1 and 2 was between 0.00 and 0.08 in all variables. Effect sizes f^2 of 0.02, 0.15, and 0.35 correspond to small, medium, and large effects, respectively (2).

	B (SE)	EXP(B)	95% CI FOR EXP(B)	f^2
Composite memory	-0.04 (0.03)	0.96	0.91 to 1.01	0.016
Psychomotor speed	-0.03 (0.01)*	0.98	0.96 to 0.99	0.074
Reaction time	0.01 (0.00)*	1.01	1.00 to 1.01	0.081
Complex attention	0.05 (0.02)	1.05	1.00 to 1.09	0.034
Cognitive flexibility	-0.04 (0.02)*	0.96	0.93 to 0.99	0.05
Processing speed	-0.05 (0.02)*	0.95	0.92 TO 0.98	0.068
VOR-gain	1.71 (2.79)	5.6	0.02 to 1301.52	0.002
DVA loss	3.01 (2.38)	20.35	0.19 to 2160.51	0.011
Sway velocity	0.15 (0.34)	1.16	0.60 to 2.25	0