Towards a Better Understanding of Children's and Adolescents' Everyday Life: Physical Activity and its Association to Executive Function and Well-Being

Dissertation

der Mathematisch-Naturwissenschaftlichen Fakultät
der Eberhard Karls Universität Tübingen
zur Erlangung des Grades eines
Doktors der Naturwissenschaften
(Dr. rer. nat.)

vorgelegt von
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Tübingen
2024

Gedruckt mit Genehmigung der Mathematisch-Naturwissenschaftlichen Fakultät der Eberhard Karls Universität Tübingen.

Tag der mündlichen Qualifikation:	04.07.2024
Dekan:	Prof. Dr. Thilo Stehle
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2. Berichterstatter/-in:	Prof. Dr. Claudia Friedrich

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List of Abbreviations

PA	Physical activity
EF	Executive function
WHO	World Health Organization
MVPA	Moderate-to-vigorous physical activity
ADHD	Attention deficit hyperactivity disorder
SES	Socio-economic status

Abstract

Living a physically active life is of central importance for physiological and psychological outcomes across the lifespan. In childhood and adolescence, previous research suggests that physical activity (PA) is beneficial for cognitive outcomes, like executive function (EF), and mental health aspects, like well-being. However, most prior examinations implemented interventional study designs, yielding information about the effectiveness of PA interventions. Such findings are not necessarily transferrable to individuals' PA in everyday life, which includes different types of PA and strongly varies between and within individuals over time. With youth's lifestyle becoming increasingly sedentary, it is important to better understand the relevance of everyday PA for psychological correlates in children and adolescents, and for this, more observational research is necessary. Ambulatory assessment presents a unique opportunity for the examination of PA, its variability in everyday life, and its relevance for psychological outcomes, allowing the examination of associations between individuals but also short-term associations within individuals.

Thus, this dissertation had three central aims: First, the focal goal was to specifically investigate *everyday PA* in children and adolescents in observational study designs. Second, this dissertation aimed to particularly examine the relevance of everyday PA in developmentally important age groups of childhood and youth. Namely, we targeted the age group of preschoolers (*Manuscript 1*), which undergoes important developmental steps in EF but has rarely been examined previously. Further, we addressed adolescents (*Manuscript 3*), representing a crucial age group in the onset of internalizing psychological symptomatology. Better understanding the relevance of PA in these age groups is important for the promotion of cognitive and mental health outcomes. Third, another main goal of this dissertation was to implement ambulatory assessment to better understand the *real-time* and *real-life* association between everyday PA and psychological correlates in childhood and youth (*Manuscript 2*, *Manuscript 3*).

In *Manuscript 1* we examined the association between accelerometer assessed everyday PA and EF performance in a test battery in a sample of 68 German preschoolers. Since results patterns in this age group have often been inconsistent, we examined hyperactive-impulsive behavior as a previously suggested moderator. We found that PA was negatively related to EF performance, and hyperactive-impulsive behavior did not moderate this association. In *Manuscript 2*, we investigated a sample of 64 German preadolescents in an ambulatory assessment study with three data collection waves of each 18 days. We measured everyday PA

with accelerometers and participants completed a task assessing EF three times per day outside of school hours in the morning, afternoon, and evening. In the morning and afternoon, we found that PA was positively related to EF between individuals but not within individuals. In the evening, we observed no association between PA and EF. This result pattern was consistent across all three data collection waves. In *Manuscript 3*, we examined how everyday PA was related to well-being during the COVID-19 pandemic in a sample of 125 German adolescents. To assess PA and well-being, participants filled out a short questionnaire in the evening for 28 consecutive days. Here, our results suggested that PA was positively related to adolescent well-being between as well as within individuals. Further, exploratory analyses revealed that PA in different contexts (i.e., leisure time, school, sports club) was distinctly related to well-being.

The findings of this dissertation yield important insights into the association between everyday PA and psychological correlates in different age groups across childhood and adolescence. Differences to study findings from interventional study designs emphasize the importance of specifically investigating PA exhibited in children's and adolescents' everyday lives with its variability, but more research is necessary. Future research should implement ambulatory assessment, as it offers unique possibilities for examining short-term within-person associations between everyday PA and psychological correlates, including the directionality of associations. Such findings can inform the development and implementation of future individualized and timely interventions for the promotion of everyday PA and its psychological correlates in childhood and youth.

German Abstract

Körperlich aktiv zu sein ist über die gesamte Lebensspanne von zentraler Bedeutung für physiologische und psychologische Faktoren. In der Kindheit und Jugend deutet bisherige Forschung darauf hin, dass körperliche Aktivität Vorteile für kognitive Merkmale wie zum Beispiel exekutive Funktionen aber auch für Aspekte mentaler Gesundheit wie Wohlbefinden haben können. Allerdings implementierten die meisten bisherigen Untersuchungen Interventionsstudiendesigns, welche Rückschlüsse über die Wirksamkeit von körperlichen Aktivitäts-Interventionen erlauben. Solche Befunde sind nicht notwendigerweise auf die körperliche Aktivität von Personen im alltäglichen Leben übertragbar, welche unterschiedliche Arten von körperlicher Aktivität einschließt und stark zwischen sowie innerhalb von Personen über die Zeit variiert. Da der Lebensstil in der Jugend immer bewegungsärmer wird, ist es wichtig, die Bedeutung von alltäglicher körperlicher Aktivität für psychologische Merkmale in der Kindheit und Jugend besser zu verstehen, und hierfür sind weitere Beobachtungsstudien nötig. Ambulantes Assessment stellt eine einzigartige Möglichkeit für die Erforschung von körperlicher Aktivität, ihrer Variabilität im alltäglichen Leben und ihrer Relevanz für psychologische Merkmale dar, weil sie die Untersuchung von Zusammenhängen zwischen Individuen aber auch von kurzfristigen Zusammenhängen innerhalb von Individuen erlaubt.

Folglich hat diese Dissertation drei zentrale Ziele: Erstens ist das hauptsächliche Ziel spezifisch *alltägliche körperliche Aktivität* bei Kindern und Jugendlichen in Beobachtungsstudien zu untersuchen. Zweitens beabsichtigt diese Dissertation die Bedeutung alltäglicher körperlicher Aktivität speziell in entwicklungsbedingt wichtigen Altersgruppen in Kindheit und Jugend zu untersuchen. Und zwar untersuchten wir gezielt die Altersgruppe von Vorschüler*innen (*Manuskript 1*), welche wichtige Entwicklungsschritte in den exekutiven Funktionen durchläuft, aber bisher selten untersucht wurde. Außerdem untersuchten wir gezielt Jugendliche (*Manuskript 3*), weil diese eine entscheidende Altersgruppe für die Entstehung internalisierender psychologischer Symptomatik darstellt. Die Bedeutung körperlicher Aktivität in diesen Altersgruppen besser zu verstehen ist wichtig für die Förderung kognitiver Merkmale und Aspekte mentaler Gesundheit. Drittens war ein weiteres zentrales Ziel dieser Dissertation Ambulantes Assessment zu implementieren, um den Zusammenhang zwischen alltäglicher körperlicher Aktivität und psychologischen Merkmalen in der Jugend *in Echtzeit* und *im wahren Leben* zu verstehen (*Manuskript 2*, *Manuskript 3*).

In *Manuskript 1* untersuchten wir die Beziehung zwischen mit Akzelerometern gemessener körperlicher Aktivität und exekutiver Funktionsleitung in einer Testbatterie in einer

Stichprobe von 68 deutschen Vorschüler*innen. Da die Ergebnismuster in dieser Stichprobe oft inkonsistent gewesen sind, untersuchten wir hyperaktiv-impulsives Verhalten als einen zuvor vorgeschlagenen Moderator. Wir fanden, dass körperliche Aktivität negativ mit exekutiver Funktionsleistung zusammenhing, und hyperaktiv-impulsives Verhalten diesen Zusammenhang nicht moderierte. In *Manuskript 2* untersuchten wir eine Stichprobe von 64 deutschen vorpubertierenden Kindern in einer ambulanten Assessment Studie mit drei je 18-tägigen Datenerhebungswellen. Wir erfassten alltägliche körperliche Aktivität mit Akzelerometern und die Studienteilnehmenden bearbeiteten drei Mal am Tag außerhalb der Schulzeit morgens, mittags und abends eine Aufgabe zur Messung der exekutiven Funktionen. Morgens und mittags fanden wir, dass körperliche Aktivität zwischen Personen aber nicht innerhalb von Personen positiv mit den exekutiven Funktionen zusammenhing. Abends fanden wir keinen Zusammenhang zwischen körperlicher Aktivität und exekutiven Funktionen. Dieses Ergebnismuster war über alle drei Datenerhebungswellen konsistent. In *Manuskript 3* untersuchten wir den Zusammenhang zwischen alltäglicher körperlicher Aktivität und Wohlbefinden während der COVID-19 Pandemie in einer Stichprobe von 125 deutschen Jugendlichen. Um körperliche Aktivität und Wohlbefinden zu erfassen, füllten die Teilnehmenden einen kurzen abendlichen Fragebogen für 28 aufeinanderfolgende Tage aus. Unsere Ergebnisse weisen hier darauf hin, dass körperliche Aktivität positiv mit jugendlichem Wohlbefinden zwischen und innerhalb von Personen zusammenhing. Außerdem ergab eine explorative Analyse, dass körperliche Aktivität in unterschiedlichen Kontexten (Freizeit, Schule, Sportverein) unterschiedlich mit Wohlbefinden zusammenhing.

Die Ergebnisse dieser Dissertation bergen wichtige Erkenntnisse bezüglich der Beziehung zwischen alltäglicher körperlicher Aktivität und psychologischen Merkmalen in unterschiedlichen Altersgruppen in Kindheit und Jugend. Unterschiede zu Ergebnissen aus Interventionsstudien verdeutlichen die Notwendigkeit, gezielt körperliche Aktivität mit ihrer Variabilität im alltäglichen Leben der Jugend zu untersuchen, wobei aber mehr Forschung nötig ist. Zukünftige Forschung sollte ambulantes Assessment implementieren, da es einzigartige Möglichkeiten für die Untersuchung von kurzfristigen Zusammenhängen zwischen körperlicher Aktivität und psychologischen Merkmalen innerhalb von Personen ermöglicht, einschließlich der Direktionalität von Zusammenhängen. Solche Ergebnisse können die Entwicklung und Implementierung von zukünftigen individualisierten und zeitnahen Interventionen für die Förderung alltäglicher körperlicher Aktivität und verbundener psychologischer Merkmale in der Kindheit und Jugend prägen.

List of Publications

This dissertation is based on the following three manuscripts:

a) Manuscripts in Preparation

Eppinger Ruiz de Zarate, A., Kerner auch Körner, J., Haas, P., Gunzenhauser, C., Rauch, W., & Gawrilow, C. (2024). Executive function and physical activity in preschoolers: Does hyperactive-impulsive behavior moderate this association? *Manuscript in Preparation*.

b) Accepted Manuscripts

Eppinger-Ruiz de Zarate, A.[*], Powell, D.[*], Kühnhausen, J., Allan, J. L., Johnstone, A., Crabtree, D. R., Buosi, W., Fyfe, C. L., McMinn, D., McCavour, B., Gawrilow, C., & Stadler, G. (2024). Free-living physical activity and executive function: A multi-study analysis of age groups and times of day. *International Journal of Clinical and Health Psychology*, *24*(1), 100425. https://doi.org/10.1016/j.ijchp.2023.100425

Eppinger Ruiz de Zarate, A., Thiel, A., Sudeck, G., Dierkes, K., John, J. M., Nieß, A. M., & Gawrilow, C. (2023). Well-being of adolescents during the COVID-19 pandemic: Ambulatory assessment of physical and sport activity, social contacts, and screen time. *Zeitschrift Für Psychologie*, *231*(2), 83–92. https://doi.org/10.1027/2151-2604/a000518

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1. General Introduction

Children's and adolescents' daily lives are composed of different activities, and *physical activity (PA)* presents a daily behavior of central importance, referring to any bodily activity that increases an individual's energy expenditure (Caspersen et al., 1985). It can vary strongly between individuals, with some children being generally more physically active than others, but also within individuals over time: On a larger time scale, differences in PA levels can be observed between seasons (Turrisi et al., 2021) and across childhood and youth (van Sluijs et al., 2021), but PA exhibited in everyday life also varies within individuals on smaller time scales, like from day to day or within the same day (Migueles et al., 2021). Across the lifespan, PA is important for physiological health outcomes (e.g., heart disease, diabetes) as well as psychological correlates, including cognitive outcomes like *executive function (EF)* (Alvarez-Bueno et al., 2017; Carson et al., 2016; Colcombe & Kramer, 2003; Donnelly et al., 2016; Verburgh et al., 2014) or mental health aspects like *well-being* (Buecker et al., 2021).

Regardless of the numerous advantages of living a physically active life, PA levels are decreasing across the globe (Guthold et al., 2018; Kohl et al., 2012), and decreases can already be observed in childhood and youth (van Sluijs et al., 2021) with most children and adolescents not meeting recommended PA levels (Bucksch et al., 2024). Accordingly, the increasing physical inactivity has been referred to as a global pandemic (Kohl et al., 2012), and in an approach to combat the increasing inactivity, the World Health Organization (WHO) declared the *Global Action Plan on Physical Activity 2018-2030* (World Health Organization, 2018). It presents a framework of effective and feasible policy actions to engage people across the globe to become more physically active, for example by creating safe environments, and it emphasizes the importance of an evidence-based practice.

However, evidence in childhood and youth is limited – with especially scarce evidence in developmentally important age groups like preschoolers – and most scientific work has implemented interventional study designs examining the effects of PA interventions. Findings from interventional study designs cannot necessarily be transferred to PA exhibited in everyday life with its strong variability between as well as within individuals. For this, ambulatory assessment study designs are especially appropriate, repeatedly measuring children's and adolescents' behavior, cognition, and emotion in *real-time* and *real-life* with high ecological validity (Bugl et al., 2015; Trull & Ebner-Priemer, 2013). With technological advances, the interest in assessing children's and adolescents' everyday PA and its psychological correlates through ambulatory assessment has increased over the last years (Reichert et al., 2020), but

more research examining everyday PA – regardless of specific PA interventions – is necessary to better understand its relevance for diverse psychological outcomes. Thereby, investigating child and youth samples is beneficial on three levels: in the present for children and adolescents, later in their adulthood, and for future generations (van Sluijs et al., 2021). Further, everyday PA presents an easy and widely applicable opportunity for (mental) health promotion and prevention (Fegert et al., 2020).

Given the numerous advantages of PA for physiological and psychological outcomes but also taking into consideration the gaps in the previous literature (e.g., limited evidence, focus on interventional studies), the central aim of this dissertation is to examine the role of *everyday PA* for different psychological correlates in childhood and youth – namely, EF and well-being. Further, this dissertation aims to explicitly examine developmentally crucial age groups in childhood and youth, and to expand the current scientific literature by implementing ambulatory assessment, allowing the examination of associations between as well as within individuals in *real-time* and *real-life*. Accordingly, *Manuscript 1* focuses on the association between everyday PA and EF in preschoolers, an important age group for EF development (Diamond, 2013; Garon et al., 2008) that has rarely been investigated in the literature (Carson et al., 2016). *Manuscript 2* employs an ambulatory assessment study with three data collection waves to investigate the association between everyday PA and EF in preadolescents at different times of day and across approximately one year. Previous research suggests that preadolescents might be especially sensitive to PA-related effects on EF (Ludyga et al., 2016), but evidence on real-time and real-life associations is very limited (Trevillion et al., 2022). *Manuscript 3* also implements ambulatory assessment, focusing on an adolescent sample during the COVID-19 pandemic, which presented a time period of risk for public (mental) health and affected adolescents in a particularly crucial developmental phase (Fegert et al., 2020). We investigated the relation between everyday PA and well-being between as well as within individuals.

In this dissertation, in chapter *2. Theoretical and Empirical Background*, I will first present the scientific background regarding everyday PA and its psychological correlates EF and well-being in childhood and youth, introduce the promising method of ambulatory assessment, and highlight gaps in the previous literature. In chapter *3. Research Aims*, I will then present the central research questions of this dissertation, followed by chapter *4. Summary of Manuscripts*, in which I will shortly introduce the manuscripts presented in this dissertation and their findings. In the last chapter *5. General Discussion*, I will discuss the main findings of the manuscripts, present methodological considerations, limitations to the scientific approach of the manuscripts, and derive directions for future research as well as practical implications.

2. Theoretical and Empirical Background

2.1. Physical Activity

2.1.1. Definition of Physical Activity

Physical activity (PA) refers to any bodily movement generated by skeletal muscles that increases an individual's energy expenditure (Caspersen et al., 1985). All individuals perform PA in their daily life, but its type and quantity can strongly differ between persons and within persons over time. *Exercise* or *sport activity* represents a subdomain of PA that is planned and characterized by a structured setting, repetition, and a specific aim (e.g., improving or maintaining fitness, performance, health). Both are positively linked to *physical fitness*, which subsumes individuals' attributes (e.g., muscular strength, endurance, flexibility) related to their ability to perform PA. All types of PA, including exercise, describe a complex behavior and its investigation requires an operational description and categorization: One component is that PA can be willful or rather compulsory, and the setting or context in which it takes place presents a second component, such as leisure time also including household tasks, school or workplace, and sports clubs. As a third component, PA can be defined by quantity, which typically entails a description of duration, frequency, or intensity. When measuring intensity, PA is typically categorized into different PA intensities ranging from sedentary, to light PA, moderate PA, and vigorous PA. Exemplary activities for the different intensities can be found in *Table 1*.

The importance of PA for numerous health indicators in childhood and youth is well-documented (Carson et al., 2017; Poitras et al., 2016), and yet people's lifestyle is becoming increasingly sedentary across the globe (Guthold et al., 2018; Kohl et al., 2012). Accordingly, living a physically active life has repeatedly been promoted for positive public health outcomes. For instance, the World Health Organization (WHO) published the *Global Action Plan on Physical Activity 2018-2030* (World Health Organization, 2018) with the aim of globally promoting PA. Amongst other recommendations, the WHO developed age-specific PA guidelines that combine aspects of PA intensity and duration: In childhood and youth, the recommendation focuses on improving fitness, coordination and movement control, and it implies that averaged across one week children and adolescents should spend at least 60 minutes per day in moderate-to-vigorous PA (MVPA). Recent results from a nationwide German survey suggest that the majority of older children and adolescents (11-15 yrs) do not fulfill these guidelines (Bucksch et al., 2024). To investigate whether these guidelines are met and what effect they have on children's and adolescents' life, it is important to measure the PA levels exhibited in everyday life, with MVPA being examined most often.

2.1.2. Physical Activity in Everyday Life

In their daily lives, children run, climb, jump, and play, thus, leading to a substantial amount of PA performed every day. Accordingly, adults observing children are often left to wonder how they can muster the energy for all their different activities and games, resulting in more or less structured PA of varying intensity levels. Across childhood and youth, the quantity and type of PA that can be observed differ vastly: Decreases in PA levels can be observed with increasing age (van Sluijs et al., 2021) and with the beginning of and transition to school (Gropper et al., 2020). To understand the relevance of PA for different physiological and psychological outcomes, it is important to consider all different aspects of PA in everyday life.

However, many previous studies investigating the effect of PA on different physiological and psychological health outcomes like cognitive functioning have implemented interventional study designs (Alvarez-Bueno et al., 2017; Carson et al., 2017; Donnelly et al., 2016; Poitras et al., 2016). Such interventions can be classified as *acute* interventions, taking place once and for a limited time (e.g., 20 minutes; Haas et al., 2022), or as *chronic* interventions, repeatedly applied over a longer time period. For example, Kamijo et al. (2011) implemented a PA intervention, lasting two hours every school day for nine months, during which participants underwent different physical fitness stations and took part in organizational games with the aim of increasing cardiorespiratory fitness and refining motor skills. A large body of research has examined the effectiveness of PA interventions, but in contrast, evidence regarding the role of PA exhibited in everyday life is limited (Wickel, 2017).

Interventional or *experimental* studies allow to investigate causal relations and are especially valuable in earlier steps of theory development (Reis, 2012). However, findings from such studies cannot necessarily be transferred to the role of everyday PA. Examining everyday PA is especially relevant to understand the role of PA independent from specific PA interventions or sportive exercises. Further, it allows to test theories derived from interventional studies about the relevance of PA in naturalistic circumstances of daily life. Further, the WHO guidelines refer to daily PA levels and emphasize the importance of an active lifestyle. To assess and examine PA in everyday life, *observational* studies are necessary. In contrast to interventional studies that often implement more structured PA (e.g., team sport), observational studies capture everyday PA, including also unstructured and non-organized PA described at the beginning of this chapter (e.g., jumping). Accordingly, everyday PA entails a wide range of types and intensities that can strongly vary between persons and within individuals over time. Interventional study designs do not account for this variability observable in everyday PA.

Hence, to better understand the role of a physically active lifestyle for individuals' physiological and psychological health, it is important to capture their everyday PA. For this, different measurement approaches have been developed. Some often-implemented reliable and valid methods for the measurement of PA will be described in the following section.

2.2. Measurement of Everyday Physical Activity

2.2.1. Subjective and Objective Measurement Methods

Over the years, different measurement methods for PA have been established that can be classified as rather *subjective* or *indirect* measures on the one hand and as rather *objective* or *direct* measures on the other hand. Subjective measures typically refer to questionnaires assessing PA. These can be either based on self-report or on observer-report, the latter often being employed in child samples where a parent or teacher would report about a child's PA. Assessing PA subjectively leads to some restrictions regarding psychometric properties: In childhood and adolescence, a systematic review compared 89 different questionnaires (Hidding et al., 2018), and the authors emphasized that validity was limited for all questionnaires, with acceptable validity only found for one questionnaire for adolescents. But importantly, questionnaires with acceptable reliability were found for all age groups (preschool, children, adolescents). Despite limitations regarding psychometric properties (e.g., reliability, validity; Hidding et al., 2018; Shephard, 2003), subjective measurement methods have the advantage that they are economical, easily applicable, and can inform the researcher about the type of PA that was performed as well as its quality (e.g., walking with or without pain). However, they are not free of bias, like social desirability or hindsight bias (Trull & Ebner-Priemer, 2013).

To discharge problems surrounding biases, objective PA measurement methods can be employed, which are believed to be more robust. With increasing technological advances, a growing number of objective methods have been developed, which can be divided into motion sensors (e.g., accelerometers, pedometers) and physiological markers (e.g., respiratory rate, heart rate monitoring). Here, I will focus on accelerometers, since accelerometers of the type Actigraph GT3X+ (Actigraph, LLC, Fort Walton Beach, Florida) were implemented in *Manuscript 1*and *Manuscript 2* of this thesis. *Accelerometers* represent a reliable and valid method for measuring PA in children and adolescents (Lynch et al., 2019; Phillips et al., 2021). Individuals can wear them on various parts of the body like hip, wrist, or ankle, and the Actigraph GT3X+ measures individuals' accelerations on three axes (up-down, forward-backward, left-right). The collected data is typically bandpass-filtered and aggregated into epoch counts (e.g., epoch length of 15 s) or to counts per minute, which are then classified into

PA intensities based on age-specific validated cut-points (e.g., Evenson et al., 2008; Freedson et al., 2005; Freedson et al., 1998; Pate et al., 2006). The cut-points applied in the manuscripts presented in this dissertation are depicted in *Table 1*. Cut-points can for example aid the investigation of adherence to the WHO guidelines, by objectively quantifying the time spent in MVPA. But to capture everyday PA and its relevance for physiological and psychological outcomes, it is recommended to rather measure the absolute amount of everyday PA instead of measuring the adherence to PA guidelines, because the latter differ strongly between different age groups (van Sluijs et al., 2021).

Table 1

Physical Activity Cut-points with Typical Activities and the Accelerometer Cut-Points Applied in the Manuscripts of this Dissertation

Intensity	Typical Activities	Accelerometer Cut-Points in this Dissertation [a]		
		Manuscript 1 preschool [b]	Manuscript 2 children 1 [c]	Manuscript 2 children 2 [d]
Sedentary	reading, coloring books	< 100	< 149	< 104
Light	walking below 4 km/h	100-1679	150-499	104-2295
Moderate	walking 4-7 km/h, stair climbing	1680-3367	500-3999	2296-4011
vigorous	cycling > 16km/h, jumping jacks	≥ 3368	≥ 4000	≥ 4012

Note. [a] for easier comparability, all cut-points were aggregated to counts per minute; [b] cut-points defined by Pate et al. (2006); [c] *Study 1* of *Manuscript 2*: cut-points defined by Freedson et al. (2005); [d] *Study 2* of *Manuscript 2*: cut-points defined by Evenson et al. (2008).

Despite their numerous advantages, objective PA measurement methods (e.g., accelerometers) have their own disadvantages and challenges. While they might be free of bias, they can lead to measurement reactivity in participants, with participants possibly increasing their usual PA levels as a result of knowing that it is being recorded. Various studies have examined this possibility across the lifespan, and a review suggested that for the measurement of MVPA most studies did not report reactivity (König et al., 2022). Still, reactivity to accelerometers cannot be completely discarded (e.g., children: Dössegger et al., 2014; adults: Ullrich et al., 2021) and needs to be considered when interpreting scientific results. They are also more expensive and time-consuming than subjective measures, and present a higher participants burden, thus, limiting their applicability in large or intensive research designs (e.g., large epidemiologic studies, ambulatory assessment; Adamo et al., 2009). In addition, objective

measurement methods yield limited or no information about the type, quality, and context of PA exhibited, for example if it is being performed in a group or alone.

Differences between subjective and objective PA measurement methods have repeatedly been reported in the literature, with individuals overestimating objectively measured PA levels in self-report (Prince et al., 2008) or parental report (Adamo et al., 2009). Thus, when comparing studies examining everyday PA, it is important to consider the measurement method used. Despite subjective and objective measurement methods often reporting a similar outcome (e.g., time spent in MVPA), the outcome itself might not necessarily be equivalent: While objective measurement methods merely reflect the time and acceleration detected by the specific device, subjective PA reports may also entail elements of the psychosocial or environmental context, perceived time-use, and intensity (Troiano et al., 2014). These differences in subjective and objective measurement methods should be considered when measuring PA and its variability in individuals' everyday life. Important theoretical and practical implications for measuring the variability of everyday PA will be presented in the next section, introducing the relevant study design of ambulatory assessment.

2.2.2. Ambulatory Assessment

It has long been emphasized that PA differs not only *between individuals*, referred to as *between-person* or *interindividual*, – with some persons being overall more physically active than others – but it also varies *within individuals* over time (Caspersen et al., 1985), referred to as *within-person* or *intraindividual*. For example, PA undergoes seasonal changes with higher MVPA levels in summer (Eppinger-Ruiz de Zarate et al., 2024; Turrisi et al., 2021), and it fluctuates across the day (e.g., activity-rest circadian patterns; Migueles et al., 2021).

To capture these fluctuations and examine the relevance of the variability of PA for other behaviors or psychological correlates in daily life, *ambulatory assessment* is especially well-suited (Reichert et al., 2020). Ambulatory assessment study designs comprise a range of different methods (e.g., observational, sensor-based, self-report) used to study individuals within their naturalistic environment (Trull & Ebner-Priemer, 2014). They repeatedly measure individuals' behavior, cognition, or emotion in close timely proximity within their daily life, thereby ensuring a high ecological validity (Bugl et al., 2015). The goal of ambulatory assessment studies is a *naturalistic* observation, allowing researchers to derivate conclusions about context-specific relationships with high applicability and generalizability (Fahrenberg, 1996). Metaphorically, ambulatory assessment provides the researchers with a detailed film of individuals' daily lives instead of granting a momentary snapshot through single assessments

at specific points in time (Shiffman et al., 2008). In contrast to laboratory experiments, ambulatory assessment studies enable us to examine individuals' daily behaviors, cognition, or emotion in *real-time* and *real-life*. For example, evidence from ambulatory assessment studies suggests that the social context like being with others and the physical context like being outdoors are associated to higher PA levels in children and adolescents (Papini et al., 2020).

Typically, ambulatory assessment methods relied on subjective measures (e.g., daily diary studies), but with increasing technological advances new measurement methods facilitate measuring facets of daily life beyond self- or observer-reported aspects through objective measurement methods, like heart rate variability or an individuals' physical location (Reichert et al., 2020; Reis, 2012). To capture the variability of PA occurring in everyday life, objective measurement methods show clear advantages in comparison to subjective measures, as objective sensors can be worn in participants' daily lives, constantly monitoring their bodily activities. For the assessment of constructs like affective states and motivation, however, self-report cannot necessarily be avoided. Given that, in contrast to objective measurement methods, self-report is subject to biases, it is a clear advantage of ambulatory assessment that retrospective biases can be eliminated through the immediate and real-time assessment. Accordingly, children's self-reported PA levels in ambulatory assessment have been reported to correspond with accelerometer-assessed PA (Dunton et al., 2011). Further, subjective and objective measures should not necessarily be viewed as contrasting measurement methods, but the combination of both in ambulatory assessment can be particularly informative. For example, different reasons and motivations for objectively-assessed PA (e.g., emotion regulation through PA, fitness goals) could be investigated by implementing self-reports (Bussmann & Ebner-Priemer, 2012). This is especially valuable in later steps of theory development: After refining theories in experimental investigations, the theories and their impact can be further examined in naturalistic circumstances through ambulatory assessment (Reis, 2012).

In addition, ambulatory assessment studies allow to separate effects found between individuals from those found within individuals. While large sample cross-sectional approaches help developing general laws by investigating the distribution of variables within a population, their applicability to individuals within this population can be investigated with ambulatory assessment studies (Hamaker, 2012). *Within-person associations* directly reflect short-term within-person processes, whereas *between-person associations* represent an indirect cumulative outcome of within-person processes (Schmiedek et al., 2020). While between-person relations can be investigated in cross-sectional study designs, short-term within-person processes can only be depicted through repeated measurement in ambulatory assessment. And specifically

examining within-person associations is important, since these can be contrary to between-person associations examined at the aggregated level. One example could be walking speed and the risk of falling in toddlers: On the between-person level, we might observe a decreased risk of falling with an increasing walking speed because of toddlers' motor development. However, on the within-person level, the relationship might be inverted, as the risk for falling increases if a toddler walks faster than normally – and possibly beyond their own abilities. Examples like this prove that within-person associations are characterized by individual differences, like the motor developmental stage of the toddler in the prior example.

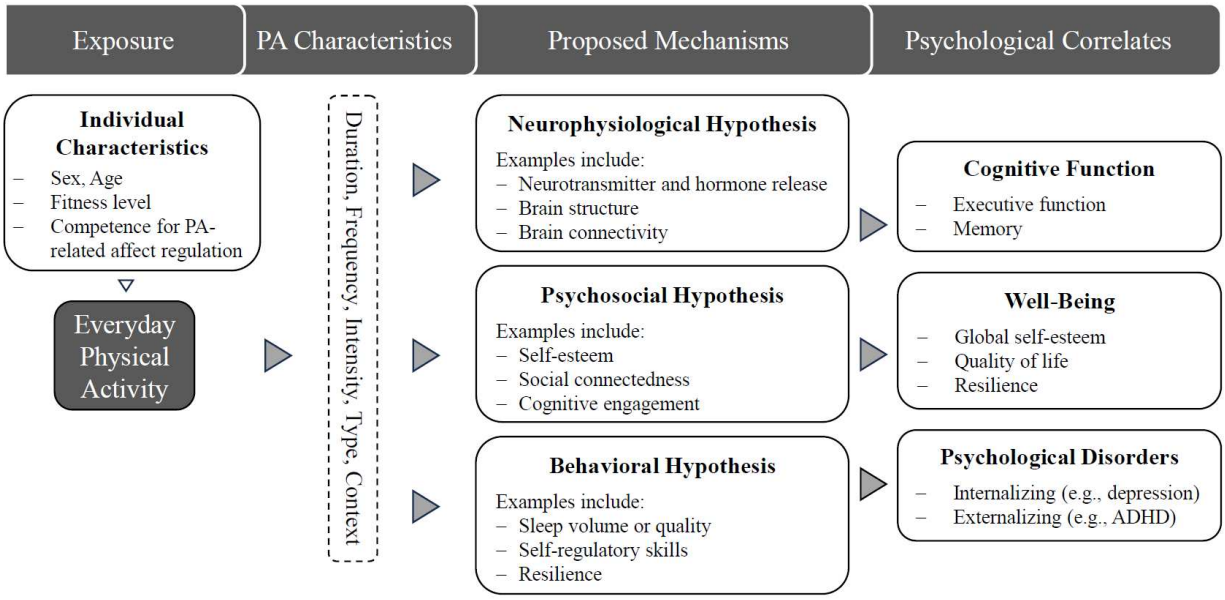
So far, only a limited number of ambulatory assessment studies have examined everyday PA in adults (Perski et al., 2022), and the number is even more limited in child and youth samples (Bourke et al., 2021; Papini et al., 2020). Yet, this literature allows first insights into the relation between PA and (mental) health outcomes as well as psychological correlates in daily life. In the following paragraphs, I will focus on two psychological correlates of PA, namely executive function and well-being, present the current scientific literature, and especially focus on ambulatory assessment studies.

2.3. Executive Function and Well-Being as Psychological Correlates of Physical Activity

Beyond beneficial effects for physiological health aspects (e.g., adiopositiy, cardiovascular biomarkers, bone health; Poitras et al., 2016), PA is also related to various psychological correlates. For example, numerous intervention studies suggest that PA can be employed as a complementary aspect in the treatment of psychological disorders, such as attention deficit hyperactivity disorder (ADHD; Montalva-Valenzuela et al., 2022; Welsch et al., 2021; Xie et al., 2021) or depression and anxiety (Oberste et al., 2020; Radovic et al., 2017; Schuch et al., 2016). In non-clinical samples, evidence further suggests positive relations between PA and mental health aspects like well-being (Biddle et al., 2019; Brown et al., 2013; Rodriguez-Ayllon et al., 2019) as well as cognitive functioning (Alvarez-Bueno et al., 2017; Carson et al., 2016; Verburgh et al., 2014). Different mechanisms are proposed in the literature linking PA to various psychological correlates (Lubans et al., 2016), which are depicted in *Figure 1*: PA can be more directly related to these psychological correlates on the *neurophysiological* level through changes in brain structure and connectivity but also hormonal release (Hsieh et al., 2018; Martikainen et al., 2013; Mora-Gonzalez et al., 2019; Wood et al., 2018). Further, PA can be more indirectly related to psychological correlates through *psychosocial* mechanisms like cognitive engagement (Best, 2010) or self-esteem (Diamond, 2012) as well as through *behavioral* mechanisms like improved sleep (Diamond, 2012).

Figure 1

Conceptual Model of Mechanisms Linking Physical Activity and Psychological Correlates Suggested by Lubans et al. (2016)



Note. Illustration adapted from Lubans et al. (2016).

Figure 1 presents the different proposed mechanisms linking PA and various psychological correlates related to mental health (Lubans et al., 2016). In the next chapters of the introduction, I will shortly introduce previously examined mechanisms and present the existing evidence regarding the relation between PA and (1) *executive function* as well as (2) *psychological well-being*. I will point out gaps in the previous literature, highlighting how this dissertation aims to close these gaps and to aid a better understanding of the importance of everyday PA in crucial developmental phases in childhood and youth.

2.3.1. Physical Activity and Executive Function

2.3.1.1. Definition and Importance of Executive Function

Executive function (EF) are a set of higher-order cognitive functions that enable individuals to regulate, organize, and direct their behaviors, cognitions, and emotions in a goal-directed manner (Barkley, 2001) – especially when this competes with an individuals' habits, impulses, or desires (Doebel, 2020). Often used as an umbrella term (Etnier & Chang, 2009; Isquith et al., 2005), EF can encompass different cognitive functions, that are typically correlated. Yet, the strength of this relation is low, suggesting that EF is a somewhat unitary construct but also consists of separable components (Etnier & Chang, 2009). In line with this, Miyake et al. (2000) defined EF in their prevalent and widely-spread *integrative model of EF* as a latent construct with three separable but somewhat correlated components: inhibition,

working memory (i.e., updating), and shifting. *Inhibition* describes an individuals' competence to inhibit a predominant, automatic, or prepotent behavior or response in favor of a less dominant response. Within the school context, a typical exemplary situation requiring inhibition would be if a student wanted to answer a teacher's question in class. The child would need to raise their hand and wait for the teacher to call them, meanwhile inhibiting the prepotent reaction to exclaim the answer. *Working memory* refers to the capacity to maintain and monitor task-relevant information in the working memory as well as to dynamically manipulate and update these representations as required. In the given example in school, the student would need to not only keep their answer in mind but also monitor the other students' answers and adapt their own answer if necessary. *Shifting*, as the most complex EF component, refers to the ability to adaptively shift between tasks or mental sets. In the given example, following another students' answer, the teacher might ask a follow-up question. The student would need to now shift between mindsets to adapt their answer, and they could possibly profit from applying the concepts asked in the previous question to the new question.

Across the lifespan, EF are of central importance, as they have a predictive value for academic achievements (Ahmed et al., 2021; Cortés Pascual et al., 2019; Deer et al., 2020), occupational achievement (Barkley & Fischer, 2011; Halleland et al., 2019), and health behaviors (Gray-Burrows et al., 2019) as well as mental health indicators (Diamond, 2013). Thus, the development of EF is a central developmental task in childhood with relevance for different outcomes across the lifespan.

2.3.1.2. Development of Executive Function in Childhood and Youth

In childhood, the development of the EF components follows differential developmental trajectories (Diamond, 2006, 2013): While first forms of inhibition and working memory (e.g., holding information in mind) can already be observed in infant years, they continue to develop across preschool age. For example, simple forms of working memory like maintaining informational representations in mind can already be observed in the first six months of life, whereas more complex working memory capacities like updating or monitoring representations become evident during the second year of life and further develop in preschool-age (Garon et al., 2008). Regarding inhibition, first forms of for example behavioral inhibition start developing in the second half of the first year, and dealing with simple conflicts also starts evolving at the end of the first year. Already at two years of age, children begin to integrate inhibition and working memory, as they start to apply rules represented in the working memory to inhibit prepotent responses. Shifting, as the most complex EF component, relies and builds on both inhibition and working memory, and thus develops somewhat later during preschool

period (Garon et al., 2008). In cases of strong conflict, however, children still show difficulties with shifting at the end of preschool-age, suggesting that it further develops across childhood.

The development of EF does not follow a linear process. Garon et al. (2008) highlight that the EF development in young children can be divided into two main stages: while the basic skills needed for EF performance (e.g., maintaining and manipulating representations in mind, inhibiting responses based on rules) are developed during the first stage until the age of three, the second stage in preschool-age between three and five is crucial for the EF development as complex skills combining the previously acquired basic skills emerge. Thus, the preschool period represents a crucial phase for EF development (Diamond, 2006; Garon et al., 2008), but if further continues through childhood and adolescence into young adulthood (Huizinga et al., 2006). This developmental trajectory is closely linked to the development of the prefrontal cortex (Fiske & Holmboe, 2019; Friedman & Robbins, 2022; Moriguchi & Hiraki, 2013).

The EF structure in younger age groups is still debated in the literature with some literature suggesting that clearly separable EF components can already be observed in preschool children (Garon et al., 2008; Miller et al., 2012; Monette et al., 2015), while other research suggests stronger evidence for a one-factor model of EF in preschool-age (Wiebe et al., 2008, 2011; Willoughby et al., 2012). In line with this, a recent meta-analysis suggests that EF appear more unidimensional in childhood and adolescence compared to adulthood (Karr et al., 2018), where the structure of EF suggested by Miyake et al. (2000) has repeatedly been replicated.

2.3.1.3. Measurement of Executive Function

As presented above for PA, EF measures can also be distinguished into rather subjective methods based on ratings or reports and rather objective methods that are usually performance-based. Typically, questionnaire-based assessments capture daily EF performance in realistic and less structured or controlled environments through self- or observer-report, whereas performance-based neuropsychological tests generally aim to assess the optimal EF performance in a structured environment and under favorable conditions, often with limited or no distraction or noise. Accordingly, a review of 20 studies with clinical and non-clinical child samples comparing subjective and objective EF measurement methods revealed that the correlations were mainly non-significant and of small magnitude (Toplak et al., 2013). Other examinations in childhood (8-13 yrs) also support a small association between subjective and objective EF measurement methods (Soto et al., 2020). Further, EF performance questionnaires and tests have distinct predictive value for academic outcomes, with EF tests showing a higher predictive validity (Soto et al., 2020). Thus, ample evidence suggests that subjective and

objective methods assess distinct but nevertheless both important aspects of EF: Toplak et al. (2013) argue that questionnaire-based assessments yield more information about rational goal pursuit within a realistic environment, also containing achievement goals with high internal motivation, while performance-based measures capture processing efficiency in an artificial context characterized by high external motivation, for example through the experimenter or examiner. This is important to consider, since a child with substantial EF dysfunction might perform adequately in a neuropsychological EF test within an optimal and well-structured surrounding, but it might encounter difficulties in exhibiting EF in challenging naturalistic environments, like for example in preschool. Hence, subjective and objective EF measures should not be used interchangeably and an integration of both might be best suited to obtain a more comprehensive understanding of a child's EF capacities (Toplak et al., 2013).

2.3.1.4. The Association Between Physical Activity and Executive Function in Childhood and Youth

Because of the importance of EF for numerous life outcomes throughout the lifespan, the investigation of ways to promote EF development as early as possible have gained increased attention and popularity in the scientific community (Takacs & Kassai, 2019). One often-discussed and often-examined possibility to foster EF is through PA. Different theoretical explanations have been presented in the literature as to why PA could be linked to EF: through neurophysiological, psychosocial or behavioral pathways (see *Figure 1*; Lubans et al., 2016). On the *neurophysiological level*, PA has been shown to not only alter brain activity (Hsieh et al., 2018; Mora-Gonzalez et al., 2019) on a shorter timeframe, but it also influences brain structure and function in the long-term and across the lifespan (Chaddock et al., 2011; Erickson et al., 2015; Valkenborghs et al., 2019). These changes in brain structure (e.g., white matter volume) have been shown to moderate the association between PA and EF (Ruotsalainen et al., 2020). On the *psychosocial level*, cognitive engagement during PA has been hypothesized as a possible linking mechanism between PA and EF (Best, 2010). In line with this argument, the extent to which PA involves aspects of mindfulness (e.g., yoga; Diamond, 2012) or multiple (sets of) rules directly influences the cognitive engagement of an individual during PA, which in turn influences their EF. For example, going for a run along a very familiar route might be less cognitively challenging and engaging than playing a competitive team sport. Not only are internal and external motivations probably higher in the second example, but following the rules and monitoring the teammates' positions, while at the same time deciding the best next steps in the sport game present a much higher cognitive load for the individual. On the *behavioral level*, one possible mechanism linking PA to EF could be individuals' sleep (Diamond, 2012; Könen

et al., 2015). Participation in PA can improve different sleep aspects like sleep duration and quality (Lang et al., 2013; Stone et al., 2013) – albeit a recent meta-analysis suggests only a weak and inconsistent association (Antczak et al., 2020) –, and positive effects of sleep improvement have repeatedly been reported for EF (Astill et al., 2012; de Bruin et al., 2017).

In the literature, numerous studies have investigated the effects of different PA interventions on EF, and reviews and meta-analyses of experimental studies support positive effects of PA interventions on EF across the lifespan (children: Carson et al., 2016; Donnelly et al., 2016; youth: Alvarez-Bueno et al., 2017; young adulthood: Verburgh et al., 2014; older adulthood: Colcombe & Kramer, 2003). In their re-analysis of 40 experimental studies, Ludyga et al. (2016) confirmed a small positive effect of PA interventions on EF, with a subgroup analyses of age groups suggesting strongest effects in preadolescents and older adults. The authors explained this with a higher sensitivity to PA in phases of developmental change. Following this explanation, stronger effects should also be expected in preschoolers because of the fast developmental changes (Diamond, 2006; Garon et al., 2008). Given the small number of investigations in preschool age, however, Ludyga et al. (2016) did not perform a separate analysis for the age group of preschoolers.

In general, compared to a growing body of literature examining PA interventions, only a limited number of studies has examined the role of everyday PA for EF in children and adolescents (Wickel, 2017) – and studies in preschool age are especially scarce (Carson et al., 2016). In the next sections, I will first focus on results from a limited number of observational studies examining everyday PA in preschoolers, followed by findings from older age groups. I will further concentrate on studies implementing accelerometers for the measurement of PA for a greater comparability with results from the manuscripts of this dissertation investigating PA and EF in childhood and youth (*Manuscript 1*, *Manuscript 2*).

Results from preschool samples regarding the association between everyday PA and EF differ depending on the specifically examined PA intensity: While for preschoolers' light PA some evidence suggests negative association with EF (Mcneill et al., 2018; Vabø et al., 2022), findings regarding moderate PA and vigorous PA yield mixed results (Bezerra et al., 2022; McNeill et al., 2020; Vabø et al., 2022). Somewhat more studies have examined MVPA in preschoolers, again yielding mixed results. Albeit some evidence suggests a positive association between MVPA and inhibition (Luo et al., 2023), with the reallocation of as little as five minutes to MVPA instead of sleep or light PA being related to better EF (Bezerra et al., 2020), most other studies conducted with preschoolers suggests no relation between MVPA and EF (Cook

et al., 2019; Mcneill et al., 2018) or a negative relation (Bezerra et al., 2020; Cook et al., 2019; Willoughby et al., 2018). Interestingly, the negative association between MVPA and EF was replicated in preschool samples with very different backgrounds, including samples with low socio-economic status (SES) from middle income countries according to the world bank classification (i.e., Brazil: Bezerra et al., 2020; South Africa: Cook et al., 2019) as well as a sample from a high income country (i.e., USA; Willoughby et al., 2018), suggesting a high generalizability of the negative association between everyday PA and EF in preschoolers.

In summary, only a very limited body of research has examined the association between everyday PA and EF in preschoolers, and findings are mixed. Since preschool age is a phase of central importance for EF development, one aim of this dissertation was to expand the previous literature in this age group to better understand how everyday PA is related to preschoolers' EF. For this, we investigated a sample of 68 German preschoolers in *Manuscript 1*. Since previous work suggested that the inconsistency in previous research findings might possibly be explained through hyperactive-impulsive behavior (Willoughby et al., 2018), we also examined this. To my best knowledge, *Manuscript 1* presents the first study investigating whether hyperactive-impulsive behavior possibly moderated the association between PA and EF in preschoolers. Thus, it yields important and novel insights into the relation and expands the current scientific understanding of mechanisms linking PA and EF in preschoolers.

Compared to preschool age, somewhat more studies have examined the association between everyday PA and EF in older children and preadolescents. Again, I will focus on observational studies implementing accelerometers for the objective measurement of PA. Despite Ludyga et al.'s (2016) finding that preadolescents might be specifically sensitive to PA-related effects on EF, most previous studies reported no association between accelerometer-assessed MVPA and EF (Aadland, Moe, et al., 2017; Pindus et al., 2016; Syväoja et al., 2014). A longitudinal study following 10-year-olds over seven months also reported that MVPA did not predict EF (Aadland, Ommundsen, et al., 2017). Only one study reported a positive association between overall PA and EF in 8- to 12-year-olds (van der Niet et al., 2015). When categorizing preadolescents into three activity groups based on objectively measured seven-day PA, another study also reported that the group with lowest PA showed lower EF than preadolescents from more active groups (Zhu et al., 2022). In adolescents, findings also suggest no association between objectively measured MVPA and EF (Pindus et al., 2015).

Given the developmental changes in childhood and youth, it is important to examine different age groups. However, increasing the comparability between studies conducted in

different age groups is critical to better understand the association between PA and EF across childhood and youth. For this, studies should implement comparable measures for PA and EF, applicable and scaled for different age groups. This was the central aim of *Study 1* in *Manuscript 2*: Here, we examined the association between objectively measured PA and EF in a sample of 68 children of a wide age range (7-17 yrs). Beyond that, we also examined the association in 144 adults (18-64 yrs) and 36 older adults (> 64 yrs), comprising a total sample of 249 participants. Across all age groups, we implemented accelerometers to capture everyday PA for seven days, and we employed the verbal fluency test of the Delis-Kaplan EF System (Delis et al., 2001) to assess EF, which has previously been scaled across the lifespan. The aim was to examine the association between PA and EF in the different age groups (children, adults, older adults). To my best knowledge, *Study 1* of *Manuscript 2* presents the largest sample with comparable and objective measures of PA and EF across the life span. Given the aim of this dissertation to specifically investigate everyday PA and its correlates in childhood and youth, however, I will focus more strongly on the *Study 2* of *Manuscript 2* specifically investigating a preadolescent sample with an elaborate ambulatory assessment study design, which I will introduce in the next section.

2.3.1.5. Ambulatory Assessment of Physical Activity and Executive Function in Childhood and Youth

Everyday PA entails many different types of PA, which should be considered when examining its association to EF. For instance, active commuting contributes a considerable amount to PA in everyday life (Martin et al., 2016; van Dijk et al., 2014). Thus, one study specifically examining the association between PA and inhibition in non-active and active preadolescent commuters to school (Domazet et al., 2016) revealed that the relation between accelerometer-assessed MVPA and inhibition differed between cyclists and non-cyclists. These findings emphasize the importance of examining PA in everyday life, including all types of more or less structed PA performed in everyday life, as for example cycling to school. As previously pointed out in this dissertation (see chapter *2.2.2. Ambulatory Assessment*), ambulatory assessment is especially appropriate to investigate PA in everyday life.

Importantly, evidence suggests that not only PA (Eppinger-Ruiz de Zarate et al., 2024; Turrisi et al., 2021) but also EF fluctuates over time (McKinney et al., 2020). The research project *Assessment of Cognitive Performance Fluctuations in the School Context (FLUX)* specifically aimed to examine the within-person fluctuations of working memory in a sample of German children (8-11 yrs) as well as its antecedents and consequences in daily life. They observed considerable within-person fluctuations in working memory performance across days

but also within the same day (Dirk & Schmiedek, 2016; Galeano Weber et al., 2018), thereby strengthening the applicability and feasibility of ambulatory cognitive assessment in preadolescent samples (Moore et al., 2017). By examining within-person fluctuations in EF, they expanded findings from previous cross-sectional studies, as they found that the within-person fluctuations in working memory were related to individual factors (e.g., sleep: Könen et al., 2015; affect: Neubauer et al., 2019) as well as external factors (e.g., perceived distrubance: Dirk & Schmiedek, 2017). This is especially important since well-established findings on the between-person level only provide limited information about the fluctuations in cognitive performance observed on the daily level (Schmiedek et al., 2020).

Regarding the within-person association between everyday PA and EF, to my best knowledge, only one ambulatory assessment study has been conducted with preadolescent children: Trevillion et al. (2022) investigated a sample of 35 British school children (7-11 yrs) across ten school days. Participants wore an accelerometer wristband and completed a working memory assessment two times per school day in the morning and afternoon. When averaging PA and EF across the entire study duration, MVPA was not related to EF performance between individuals. The time spent in MVPA in the two hours prior to the working memory assessment was also not immediately related to EF within individuals. Interestingly, when investigating the association between time spent in MVPA on one day and EF on the subsequent day, they observed a negative within-person association. Thus, more MVPA on the prior day was related to lower working memory on the subsequent morning. Since there was no between-person association between MVPA and EF but simultaneously prior-day MVPA was related to subsequent working memory on the within-person level, this result pattern highlights the importance to examine the relation between everyday PA and EF with ambulatory assessment on different time scales and to differentiate effects found between individuals from those found within individuals, which could enhance our understanding of how PA and EF are related in the everyday life of children.

Given the very restricted number of ambulatory assessment studies examining everyday PA and EF in children, in *Study 2* of *Manuscript 2* we aimed to expand our scientific understanding, by conducting an ambulatory assessment study with 64 German preadolescents (10-13 yrs). The study consisted of three data collection waves of each 18 days (i.e., intensive longitudinal measurement burst design), spanning over approximately one year. We measured PA with an accelerometer during the entire data collection period, and three times per day participants completed the same spatial working memory task previously employed in the FLUX project, showing sufficient variability in a slightly younger age group (Dirk &

Schmiedek, 2016; Galeano Weber et al., 2018). The aim was to examine the link between everyday PA and EF at different times of the day, and to examine the stability of these relations over the three data collection waves. To my best knowledge, this was the first study to examine everyday PA and EF multiple times per day – also outside school hours and on weekends – and across a longer time span with an intensive longitudinal measurement burst design.

2.3.2. Physical Activity and Well-Being

Previous work examining psychological correlates of PA has also focused on mental health aspects, where a main focus has been laid on internalizing symptomatology, with numerous findings supporting beneficial effects of PA interventions in the treatment of depression and anxiety in clinical samples (Oberste et al., 2020; Radovic et al., 2017; Schuch et al., 2016) as well as in non-clinical youth samples (Biddle et al., 2019; Brown et al., 2013; Rodriguez-Ayllon et al., 2019). In addition, research also suggests a beneficial effect of PA interventions for externalizing symptomatology, reporting that children with ADHD benefit from PA interventions in regards to their symptomatology (Xie et al., 2021) as well as their emotion and mood (Cornelius et al., 2017). However, interventional studies examining the effect of PA on adolescent mental health are often methodologically weak (van Sluijs et al., 2021). Since internalizing disorders have a typical onset in adolescence (Rapee et al., 2019), it is especially important to investigate the preventative potential of everyday PA in non-clinical youth samples with observational studies. Hereby, besides examining internalizing or externalizing symptomatology, research should also concentrate on positive health-related outcomes like psychological well-being (Buecker et al., 2021).

2.3.2.2. Association Between Physical Activity and Well-Being in Youth

Psychological well-being is a broad concept that has been differently defined in the literature. Generally, it refers to an individuals' evaluation of their own life considering overall life satisfaction, emotional responses, as well as domain-specific satisfaction (e.g., health-related) (Diener, 1984; Diener et al., 1999). For a more specific definition of well-being, three levels of distinction have been suggested (Lischetzke & Eid, 2006): First, two components of well-being can be distinguished, namely the *cognitive* component (i.e., individual cognitive evaluation of one's life) and the *affective* component concerning an individual's affective reaction to specific events. Second, well-being can be characterized as *domain-specific* or *global*. Third, well-being can be described on three different time frames, with *momentary* well-being at a specific moment in time, *state* well-being which is suspect to both momentary and trait-like influences, and *trait* well-being, describing an individual's stable and context-

independent general well-being. This level of distinction already implies the necessity to not only investigate well-being as a trait-like construct with cross-sectional study designs, but to also consider its fluctuations – for example, in ambulatory assessment.

Well-being is fundamentally important for mental health, and ample evidence suggests a positive link between PA and well-being in youth (Buecker et al., 2021). Comparable to explanations for the link between PA and EF, there are different mechanisms explaining the relation between PA and well-being (see *Figure 1*; Lubans et al., 2016). On the *neurophysiological level*, engaging in PA influences and improves the functioning of the hypothalamus-pituitary-adrenal axis, reducing cortisol levels and thus also reducing the physiological reaction to psychosocial stress (Martikainen et al., 2013; Wood et al., 2018). Some evidence also supports the theory that PA increases the release of endorphins, linked to increased mood during or after exercise, an effect commonly referred to as 'runner's high' (Dishman & O'Connor, 2009). On a more indirect route, *psychosocial mechanisms* (e.g., perceived self-efficacy, increased self-esteem) as well as *behavioral mechanisms* (e.g., improved sleep, reduced sleepiness) may explain the link between PA and well-being (Diamond, 2012; Lubans et al., 2016). A systematic review of interventional studies with school-aged children and adolescents revealed that PA interventions had beneficial effects on psychosocial mechanisms as well as mental health outcomes (e.g., well-being, quality of life; Lubans et al., 2016). For example, one study reported that a 12-week PA program for preadolescents improved their self-concept and mood, with improvements in self-concept being related to less negative mood (Annesi, 2005). Further, a positive association between PA and well-being could be mediated through adolescents' resilience, as a study reported that self-reported everyday PA was positively related to their resilience, which in turn was linked to higher well-being (Ho et al., 2015).

Most studies examining the relationship between everyday PA and mental health aspects in non-clinical samples have focused on the absence of symptomatology, rarely targeting positive health-related outcomes like well-being (Buecker et al., 2021). Further, only a small fraction of previous studies has examined youth samples, with adolescent samples being investigated somewhat more often than younger samples (Buecker et al., 2021; Hinkley et al., 2014). When implementing accelerometers for the measurement of PA, one observational study reported that vigorous PA was related to more positive and less negative affect in adolescents (Costigan et al., 2019), while another study reported that neither overall PA levels nor MVPA assessed in preadolescence was related to well-being three years later (Bell et al., 2019). When implementing both accelerometers and questionnaires for the measurement of PA, one study

observed that questionnaire-assessed PA was related to higher positive affect and lower negative affect in adolescents, while accelerometer-assessed PA was only related to lower negative affect (White et al., 2018). This finding, again, suggests that it is important to distinguish between findings from studies implementing different PA measures. Yet, only a limited number of observational studies employed accelerometers previously when investigating the association between PA and mood or well-being in youth (Buecker et al., 2021). Large-scale observational studies assessing PA through questionnaires in samples of over 1,000 adolescents yield a more consistent result pattern, suggesting a positive association between PA and adolescent well-being (Kirkcaldy et al., 2002; McMahon et al., 2017).

2.3.2.2. Ambulatory Assessment of Physical Activity and Well-Being in Youth

Despite an increasing number of (mainly interventional) studies examining the link between PA and well-being in youth, still to this date, there is a limited understanding of the temporal pattern of the association and how fluctuations in everyday PA over time influence its relation to well-being. First evidence examining the association between PA levels across different time scales (i.e., whole week, weekday school-time, weekday leisure-time, weekend) and well-being four months later yielded inconsistent findings, as results failed to reach significance after controlling for baseline well-being (Alshallal et al., 2024). Still, the study yields interesting insights into the association between PA and well-being on different timescales, which should be further investigated.

For this, ambulatory assessment studies are particularly well-suited, since they repeatedly measure adolescents' PA and well-being. Further, they are especially valuable when examining mental health aspects and well-being in youth, because they allow testing within-person associations, which could otherwise not be examined (Russell & Gajos, 2020). Accordingly, the number of ambulatory assessment studies investigating adolescent well-being has increased in the recent years (Russell & Gajos, 2020), but to my best knowledge, still no ambulatory assessment study has investigated the association between PA and well-being in adolescents. Instead, one study investigated the association to quality of life and found a positive within-person association with accelerometer-assessed PA as well as a positive between-person association with questionnaire-assessed leisure-time PA (Bourke et al., 2022). Closely related to well-being, a systematic review found that up to 2020 only ten ambulatory assessment studies had investigated PA and mood in children and adolescents (Bourke et al., 2021). Findings from these consistently supported a positive within-person association between PA and subsequently measured positive affect. For example, in a sample of young women (12-26 yrs), Langguth et al. (2016) found that more MVPA on the previous day predicted decreased

depressive mood on the following day. In an eight-day ambulatory assessment study measuring children's affect (9-13 yrs) seven times per day, accelerometer-assessed MVPA in the 30 minutes prior was related to more positive affect, less negative affect, and feeling more energetic (Dunton et al., 2014). At the same time, feeling less energetic and more tired resulted in lower levels of MVPA in the 30 minutes following the questionnaire administration, implying a somewhat bidirectional association between MVPA and affect in children. Another ambulatory assessment study also supported a short-term reciprocal association between accelerometer-measured PA and happiness, as PA predicted subsequent happiness and happiness also predicted PA in the subsequent hour (van Woudenberg et al., 2020). On a larger timescale (e.g., subsequent day) these effects could not be observed, highlighting the importance of examining PA and its correlates – including both precursors and consequences – on smaller time scales with ambulatory assessment studies.

2.3.2.3. Importance during the COVID-19 Pandemic

Investigating the association between everyday PA and adolescent well-being became especially important during the global COVID-19 pandemic beginning in 2020, since possibilities for performing PA were strongly limited in this time. The WHO proclaimed a global pandemic in 2020, and to prevent the spreading of the infectious disease and protect vulnerable groups of people, restrictions and social isolation measures were enforced across the globe. These measures, however, put the public – including the groups to be protected – under immense psychological stress, possibly suffering declines in physical health due to increased physical inactivity (Thiel et al., 2021). Already early in the pandemic trajectory, researchers and practitioners highlighted these restriction-related risks for public (mental) health – especially for youth since they were affected in a particularly crucial developmental phase (Fegert et al., 2020). Accordingly, increases in adolescent depressive symptomatology (Jones et al., 2021; Racine et al., 2021) as well as decreases in well-being in youth (Meherali et al., 2021; Orgilés et al., 2020) were reported after the pandemic onset and the implementation of pandemic-related restrictions. Changes in well-being were found to be related to perceived pandemic-related effect on lifestyle (de France et al., 2022) – as for example, limited possibilities for youth to engage in PA. Consequently, decreased PA levels across the globe (Kharel et al., 2022; Stockwell et al., 2021) were negatively related to well-being in youth (Bozzola et al., 2023; Cosma et al., 2021; Marckhoff et al., 2022) as well as more mental health problems (Ghorbani et al., 2021). Yet, such investigations mostly relied on cross-sectional study designs, with PA and well-being rarely being repeatedly assessed in youth's everyday life.

Previously, one ambulatory assessment study (Zubek et al., 2022) assessed PA and adolescent mood daily over two weeks during the COVID-19 pandemic and found that PA was related to better mood. Another study weekly measuring PA and happiness over a 22-week period observed declines in both PA and happiness after the pandemic onset (Munasinghe et al., 2020). However, no ambulatory assessment study specifically examined the association between PA and well-being in youth during the COVID-19 pandemic. Hence, in *Manuscript 3*, we aimed to examine the relation of PA with well-being in adolescents. We also examined the role of other daily behaviors affected by pandemic-related restrictions (i.e., screen time, social contacts), including possible interrelations between the different daily behaviors. For this, we collected data from a sample of 125 German adolescents (aged 11-20 yrs) over a one-month-period with daily evening questionnaires. We assessed the affective component of global state well-being (Lischetzke & Eid, 2006), and were specifically interested in examining whether PA in different contexts (i.e., leisure time, school, sports clubs) was differently related to adolescents' well-being. To my best knowledge, *Manuscript 3* presented in this dissertation is still to this date the only ambulatory assessment study to examine the association between everyday PA and adolescent well-being during the COVID-19 pandemic.

3. Research Aims

Based on the presented theoretical and empirical background, the overarching goal of this dissertation is to enhance our understanding of the role of everyday PA for psychological correlates in crucial developmental phases of childhood and youth. More precisely, I aim to expand prior research findings (a) through the explicit examination of *PA exhibited in everyday life* (all manuscripts), (b) through the investigation of *developmentally important age groups* that have rarely been examined previously (*Manuscript 1*, *Manuscript 3*), and (c) through the implementation of *ambulatory assessment* to measure everyday PA and its variability in the daily life of youth (*Manuscript 2*, *Manuscript 3*). The manuscripts presented in this dissertation with their research questions all contribute distinctly to the central aims of this dissertation.

Manuscript 1 investigates the association between everyday PA and EF in preschoolers, because preschool-age is a crucial stage in the development of EF that has rarely been examined in prior studies, and those studies yield mixed findings. Possible explanations for inconsistent findings could be differences in the implemented measures, but also that hyperactive-impulsive behavior moderates the association between PA and EF. *Manuscript 1* addresses both hypothesized explanations and yields important practical as well as methodological implications for future research. The investigated research questions are the following:

(1) How is everyday PA associated to EF performance in preschoolers?

(2) Does hyperactive-impulsive behavior moderate the association between everyday PA and EF in preschoolers?

(3) How are objective and subjective measures of everyday PA and EF, respectively, related?

Manuscript 2 is a multi-study analysis of the association between everyday PA and EF in different age groups (Study 1) and different times of day (Study 2). *Study 1* examines the association between PA and EF in different age groups across the life span (children, adults, older adults), implementing analogous measures for PA and EF across all age groups. This enables the direct comparison of the association across the lifespan. However, in line with the focus of this dissertation on everyday PA and its psychological correlates in childhood and youth, I will mainly focus on *Study 2* in this work. *Study 2* implements an ambulatory assessment study design with three data collection waves spanning approximately one year (i.e., intensive longitudinal measurement burst design) to examine the association between everyday PA and EF in a preadolescent sample. In preadolescents, EF might be especially susceptible to

PA-related effects because of developmental changes. Yet, only a limited body of research has examined the role of everyday PA rather than PA interventions, and most previous studies relied on between-person comparisons. Further, little is known about the association on different time scales and within a naturalistic setting. Ambulatory assessment studies are fundamental to investigate the real-time and real-life association between everyday PA and EF in preadolescents within as well as between individuals. Findings from such studies improve the scientific understanding of the relation between everyday PA and EF on different levels (e.g., within vs. between individuals, different time scales) and yield important practical implications for health promotion. The research questions of *Study 2* of *Manuscript 2* are the following:

(1) How is everyday PA related to EF in preadolescents between individuals across all assessments?

(2) How is everyday PA related to EF in preadolescents within individuals across different times of day?

(3) How stable are the relations between everyday PA and EF in preadolescents found within and between individuals across multiple data collection waves (i.e., bursts)?

Manuscript 3 also implements an ambulatory assessment study design spanning one month to examine the relation between everyday PA and well-being in adolescents. Investigating this association in adolescents is of central importance, since adolescence is a crucial developmental phase for the onset of internalizing disorders. PA represents an inexpensive and easily applicable possibility to promote well-being and mental health in this developmental phase. However, more ambulatory assessment studies are necessary to investigate this hypothesized positive association between everyday PA and well-being in adolescents' daily lives. *Manuscript 3* represents the first ambulatory assessment study examining this association within the context of the COVID-19 pandemic, yielding important practical conclusions about the importance of enabling opportunities for PA to promote adolescent well-being. The examined research questions of *Manuscript 3* are the following:

(1) How is everyday PA related to well-being in adolescents between individuals across all assessments?

(2) How is everyday PA related to well-being in adolescents within individuals and within the same day?

(3) Is PA in different contexts (i.e., leisure time, school, sports clubs) distinctly related to well-being in adolescents?

4. Summary of Manuscripts

4.1. Manuscript 1: Executive Function and Physical Activity in Preschoolers: Does Hyperactive-Impulsive Behavior Moderate this Association?

Eppinger Ruiz de Zarate, A., Kerner auch Körner, J., Haas, P., Gunzenhauser, C., Rauch, W., & Gawrilow, C. (2024). Executive function and physical activity in preschoolers: Does hyperactive-impulsive behavior moderate this association? *Manuscript in Preparation*.

Objective. Previous experimental research suggests a positive association between executive function (EF) and physical activity (PA). Observational research specifically examining PA in everyday life does not consistently support this positive association, with findings often yielding negative or no associations. Hyperactive-impulsive behavior could act as a possible moderator, explaining inconsistent findings.

Method. In this observational study, we examined the relation between EF and everyday PA as well as hyperactive-impulsive behavior as a potential moderator in a sample of 68 German preschoolers (3-5 yrs). To objectively measure EF and PA, participants performed a computerized EF test battery (EF Touch) in two sessions and wore an accelerometer for seven days. Parental questionnaires were employed as subjective measures of EF, PA, and hyperactive-impulsive behavior.

Results. We only observed an association between objective and subjective measures of EF. Objectively measured moderate-to-vigorous PA was negatively related to EF performance, and hyperactive-impulsive behavior did not moderate this association. Neither time spent in any other PA intensity nor parental PA reports were related to EF performance.

Conclusion. The findings yield new insight into the relation between PA in everyday life and preschoolers' EF, as the unexpected negative relation could not be explained through hyperactive-impulsive behavior. Our results are discussed considering methodological limitations, and possible directions in future research (e.g., combining objective and subjective measures of PA) are presented.

This abstract was retrieved from the original *Manuscript 1* (see *Appendix A*).

4.2. Manuscript 2: Free-Living Physical Activity and Executive Function: A Multi-Study Analysis of Age Groups and Times of Day

Eppinger-Ruiz de Zarate, A.[*], Powell, D.[*], Kühnhausen, J., Allan, J. L., Johnstone, A., Crabtree, D. R., Buosi, W., Fyfe, C. L., McMinn, D., McCavour, B., Gawrilow, C., & Stadler, G. (2024). Free-living physical activity and executive function: A multi-study analysis of age groups and times of day. *International Journal of Clinical and Health Psychology*, *24*(1), 100425. https://doi.org/10.1016/j.ijchp.2023.100425

Objective. Executive Function (EF) is a potential mechanism linking physical activity (PA) and mental health. However, evidence regarding the association between free-living PA and EF is limited with mixed results. Across two studies, we examined associations between accelerometer-assessed moderate-to-vigorous PA (MVPA) and facets of EF in different age groups (Study 1) and at different times of day (Study 2).

Method. In Study 1, we tested the association between MVPA and verbal fluency across seven days in 285 par- ticipants (children, adults, older adults). In Study 2, we tested between- and within-person associations between MVPA and working memory (afternoon, evening, next morning) across three 18-day bursts in 64 preadolescents.

Results. Study 1 showed no association between MVPA and verbal fluency overall, but there was an interaction by age group: a positive association was evident in older adults only. In Study 2, we observed a positive between- person association between MVPA and subsequent afternoon and next morning working memory, but not within- person. In the evening, MVPA was not related to working memory.

Conclusion. The association between free-living PA and EF differs between age groups and times of day. Future research should consider these factors when examining the association and its role for mental health.

This abstract was retrieved from the original *Manuscript 2* (see *Appendix B*).

[*] Shared first authorship

4.3. Manuscript 3: Well-Being of Adolescents During the COVID-19 Pandemic: Ambulatory Assessment of Physical and Sport Activity, Social Contacts, and Screen Time.

Eppinger Ruiz de Zarate, A., Thiel, A., Sudeck, G., Dierkes, K., John, J. M., Nieß, A. M., & Gawrilow, C. (2023). Well-being of adolescents during the COVID-19 pandemic: Ambulatory assessment of physical and sport activity, social contacts, and screen time. *Zeitschrift Für Psychologie*, *231*(2), 83–92. https://doi.org/10.1027/2151-2604/a000518

Objective. During the COVID-19 pandemic, implemented social distancing measures led to behavioral changes and decreased well-being in adolescents. The aim of this study was to examine the relation between daily behaviors (physical and sport activity, social contacts, screen time) and adolescent well-being.

Method. For this, we conducted a 28-day ambulatory assessment study. Daily data of 125 German adolescents (11–20 years) were collected every evening through self-report and analyzed with multilevel models.

Results. Between and within individuals, physical activity was positively related to well-being and screen time was negatively related to well-being. Social contacts were positively related to well-being within individuals. Explorative analyses revealed differences between sport activity contexts (sports club, leisure time, school), and between in-person and digital social contacts.

Conclusion. Our findings suggest that physical activity and in-person social contacts are positively related to adolescent well- being and should, thus, be enabled during the pandemic. Furthermore, the role of screen time should be considered in health promotion.

This abstract was retrieved from the original *Manuscript 3* (see *Appendix C*).

5. General Discussion

Living a physically active life has diverse advantages for physiological and mental health. Yet, across the globe, people's lifestyle is becoming increasingly sedentary – already in youth. Numerous previous research findings suggest positive effects of PA for different mental health aspects in youth, including cognitive functioning and well-being. However, most of these studies have implemented experimental study designs, thereby investigating the effect of specific PA interventions. Findings from such studies cannot necessarily be transferred to PA exhibited in everyday life, since the latter includes different and possibly less structured types of PA and strongly varies between as well as within individuals over time. The scientific understanding of how everyday PA is related to psychological correlates in youth is limited, and evidence is scarce in age groups undergoing important developmental steps, like preschoolers. Ambulatory assessment presents a unique possibility for the investigation of the relevance of everyday PA in real-time and real-life, and should, thus, be implemented more often in future research.

Taking into consideration the previously presented theoretical and empirical background as well as the highlighted gaps in the previous literature, this dissertation had the following aims: The first aim was to specifically examine everyday PA in childhood and youth with observational study designs instead of examining PA interventions. The second aim was to examine developmentally crucial age groups in childhood and adolescence with limited previous investigation (e.g., preschoolers). Third, another central aim of the dissertation was the implementation of ambulatory assessment to investigate between- as well as within-person associations between everyday PA and psychological correlates on different time scales and with high ecological validity.

In the following sections of the discussion, I will present and discuss the main results from the three manuscripts presented in this dissertation and highlight important methodological considerations. Hereby, I will mainly focus on the results relevant to the main goals of the dissertation, and mention additional findings (e.g., concerning other hypotheses of the manuscripts) only briefly. Then, I will focus on limitations of the presented manuscripts and, consequently, highlight possible directions for future research. I will then derive theoretical as well as practical implications from the findings of this dissertation.

5.1. Summary and Discussion of Main Results

This dissertation addresses everyday PA in childhood and youth and its relation to psychological correlates by implementing different observational study designs. For this, I presented three manuscripts that yielded the following main results: First, everyday PA is negatively related to EF in preschoolers, and this association is not moderated by hyperactive-impulsive behavior (*Manuscript 1*). Second, everyday PA is positively related to EF in preadolescents on the between-person level but not within individuals, and the association differs between times of day (*Study 2* of *Manuscript 2*). And third, everyday PA is positively related to adolescent well-being between as well as within individuals, but the relation differs depending on the context in which PA is performed (*Manuscript 3*). In the following, I will address and discuss the central research questions previously introduced in the chapter *3. Research Aims* and integrate the results of the presented manuscripts.

5.1.1. Main Results of Manuscript 1: Everyday Physical Activity and Executive Function in Preschoolers

To expand the previous scientific understanding of the association between everyday PA and EF in preschoolers, in *Manuscript 1*, we measured preschoolers' everyday PA objectively for seven consecutive days with an accelerometer. We also implemented a parental questionnaire as a subjective measurement method (Bayer et al., 2012), which I will discuss more thoroughly in chapter *5.2.1. Subjective and Objective Measurement of Everyday Physical Activity*. To objectively assess preschoolers' EF performance, we implemented a novel and extensive computerized EF test battery, recently adapted for German preschoolers (EF Touch; Ulitzka et al., 2023; Willoughby & Blair, 2011). The EF Touch was designed to measure preschoolers' EF with seven subtests, assessing the three EF components inhibition, working memory, and shifting (Miyake et al., 2000). The differentiation of the three EF components in preschool age has previously been discussed in the literature (Garon et al., 2008; Karr et al., 2018; Willoughby et al., 2012), but Ulitzka et al. (2023) found support that the German version of the EF Touch sufficiently differentiates between the hypothesized EF components. However, the model with three EF components did not improve data prediction compared to the one-factor model with a general EF component. Accordingly, *Manuscript 1* mainly focuses on the overall EF performance of 68 German preschoolers in the EF Touch in relation to their PA.

When examining the proportional time preschoolers spent in MVPA across the seven measurement days, we found a negative association with their overall EF performance: Preschoolers who spent more time in MVPA performed overall worse in the EF Touch. Our

finding replicates the results from Willoughby et al. (2018), who examined the association between accelerometer-assessed five-day PA and EF measured with the EF Touch in a sample of US preschoolers. Nevertheless, the result pattern contradicted our expectations, as it differed from findings presented a meta-analysis of seven studies in early childhood (Carson et al., 2016) suggesting a positive association between EF and PA. More importantly, the authors emphasized that no studies reported detrimental effects of PA on EF. However, the meta-analysis mainly included experimental studies focusing on PA interventions rather than everyday PA in children. Further, only one observational study included in the meta-analysis examined time spent in MVPA – and explicitly during a recess session (Becker et al., 2014); thus, examining PA during a specific context that is not necessarily transferrable to other contexts of preschoolers' daily lives. The discrepancy between findings from experimental studies and findings from our observational study as well as Willoughby et al.'s (2018) emphasizes again that results obtained from different study designs are not comparable and that it is important to consider the context in which PA is investigated (Becker et al., 2014). PA interventions often include more structured types of PA, and positive effects of such interventions on EF have repeatedly been reported across the lifespan (Alvarez-Bueno et al., 2017; Colcombe & Kramer, 2003; Donnelly et al., 2016; Verburgh et al., 2014) as well as for preschool age in particular (Carson et al., 2016). In contrast, PA exhibited in everyday life entails different and also less structured types of PA, and it is subject to high variability – especially in preschool-aged children, since they often engage in short bouts of PA with highly variable intensities (de Bock et al., 2010).

Consequently, studies investigating the association between objectively measured PA in preschoolers' everyday life and their EF yield more inconsistent results, with some reporting no associations (Cook et al., 2019; Mcneill et al., 2018) and others reporting positive associations (Luo et al., 2023). Two studies examining preschool samples from middle income countries (according to the world bank classification; i.e., Brazil, South Africa) with low SES (Bezerra et al., 2020; Cook et al., 2019) reported a negative association between MVPA and EF, in line with our findings. This suggests a high generalizability of the result pattern observed in our study, since *Manuscript 1* and the study conducted by Willoughby et al. (2018) investigated Western samples from higher income countries, also reporting a negative association. Still, the body of literature examining everyday PA and EF in preschoolers with observational study designs is very limited. The association between everyday PA and EF as well as its directionality is not yet fully understood in preschoolers. Various possible moderators that could explain inconsistent research findings are discussed in the literature, like for example

hyperactive-impulsive behavior (Gapin & Etnier, 2010; Hoza et al., 2020; Willoughby et al., 2018).

As a possible explanation for the negative association between MVPA and EF in preschoolers, Willoughby et al. (2018) suggested hyperactive-impulsive behavior as a moderator: Higher levels of hyperactive-impulsive behavior might be linked to higher PA levels and more time spent in MVPA (Bundgaard et al., 2018; Burley et al., 2022; de Crescenzo et al., 2016; Kofler et al., 2016), and preschoolers with higher hyperactive-impulsive behavior potentially engage in different types of PA (e.g., more swinging, jumping; Howie et al., 2013). Willoughby et al. (2018) argue that the types of PA that preschoolers with high levels of hyperactive-impulsive behavior engage in might be less beneficial for EF (for a further discussion of the relevance of type of PA see *5.3. Limitations and Directions for Future Research*). In contrast, other lines of research have argued that PA might be especially beneficial in individuals with high levels of hyperactive-impulsive behavior (Gapin & Etnier, 2010; Hoza et al., 2020), as these children might compensate for lower EF capacities through higher PA levels (Rapport et al., 2009). One study examining a sample of young children (aged 5-7 yrs) with developmental difficulties – and specifically with early ADHD symptoms – found that PA levels increased during a task with high EF load, and the association between increased PA and EF performance was stronger in children with higher levels of hyperactive-impulsive behaviors (Burley et al., 2022). This supports a moderating effect of hyperactivity on the relation between PA exhibited during cognitively challenging tasks and EF performance in those tasks. However, it is not clear how these findings can be transferred to PA exhibited in everyday life. To this date, to my best knowledge, no other study has yet examined whether hyperactive-impulsive behavior influences the relation between everyday PA and EF in preschoolers. Thus, *Manuscript 1* represents the first study testing this hypothesis in a preschool sample, and its results do not support any moderating effect of hyperactive-impulsive behavior. Thus, the negative relation between time spent in MVPA in everyday life and preschoolers' EF performance did not depend on the level of exhibited hyperactive-impulsive behavior – regardless of whether children showed high or low levels of hyperactive-impulsive behavior.

In summary, the results from *Manuscript 1* extend the previous body of literature regarding the relationship between everyday PA and EF (a) by specifically examining the relationship in a sample of preschool-aged children, (b) by objectively measuring everyday PA in their daily life with an accelerometer, and (c) because it is the first study to investigate a possible moderating effect of preschoolers' hyperactive-impulsive behavior.

5.1.2. Main Results of Manuscript 2: Everyday Physical Activity and Executive Function in Older Children

Another central aim of this dissertation was to implement ambulatory assessment studies to better understand the *real-time* and *real-life* association between everyday PA and EF. Accordingly, we implemented an ambulatory assessment study with three data collection waves lasting 18 days each and approximately six months apart in *Study 2* of *Manuscript 2*. Preadolescents' everyday PA was objectively measured with accelerometers and they performed a spatial working memory task (Dirk & Schmiedek, 2016; Galeano Weber et al., 2018) three times per day outside school hours in the morning, afternoon, and evening. For each time of the day, we conducted separate analyses to examine the association between everyday PA and EF on different time scales. For the associations within the same day (afternoon, evening), we summarized time spent in MVPA on the correspondent day until the minute before the EF-assessment. For the lagged analysis investigating the relation between prior day PA and next-morning EF, we summarized time spent in MVPA on the full prior day between 6am and 11pm. The separate analyses revealed a positive between-person association between MVPA and subsequent afternoon as well as next morning EF, but we observed no within-person associations. Thus, preadolescents who were overall more physically active in the time periods prior to the EF assessment performed better on the working memory task assessing EF in the afternoons, and preadolescents who spent overall more time in MVPA showed better EF performance in the mornings. In the evening, MVPA was not related to EF – neither between nor within individuals. This result pattern did not significantly change between the three data collection waves, implying stable associations across the whole study duration.

Our finding that between individuals MVPA was positively related to preadolescents' EF in the afternoons and mornings is in line with some previous research suggesting positive between-person associations (van der Niet et al., 2015; Zhu et al., 2022). Interestingly, this was not the case for the EF assessment in the evening, as we found no between-person association between MVPA and EF. This is in line with other previous research also suggesting no association between MVPA and EF (Aadland, Moe, et al., 2017; Pindus et al., 2016; Syväoja et al., 2014). However, in children, EF is typically not measured in the evenings, and the question arises to which extent previous results can be transferred to our evening assessment. Instead, our findings suggest that it is important to distinguish between the time of day when examining the relation between everyday PA and EF. In the evening, it is likely that individuals might experience increased fatigue after being more physically active (Haas et al., 2017), which could possibly explain a different association compared to other times of day. However, our

findings cannot support this explanation since we observed no significant within-person association in the evening in *Study 2* of *Manuscript 2*. To my best knowledge, only one other ambulatory assessment study investigated the relation between PA and EF in preadolescents and observed distinct short-term within-person associations across different times of day (Trevillion et al., 2022): The authors reported no within-person association between afternoon EF and MVPA in the two hours previous to the EF assessment, while prior day MVPA was negatively related to next morning EF within individuals. Hence, although the evidence about the real-time and real-life association between PA and EF in youth is still very limited, first evidence suggests that it varies across the day, which is also supported by our results.

In addition, the particular study design applied in *Study 2* of *Manuscript 2* allows to specifically investigate the stability of observed effects over several months in preadolescence and is to my understanding the first intensive longitudinal measurement burst design examining the association between PA and EF. In general, ambulatory assessment study designs yield new insight into the link between everyday PA and EF in close timely proximity and in a naturalistic setting, allowing the investigation of whether findings from interventional studies can be transferred to the daily life. Beyond that, our implemented study design provides information about changes in short-term within-person associations across wider time spans. Our findings suggest that in an age group that appears to be especially sensitive to PA-related effects on PA because of developmental changes (Ludyga et al., 2016), PA is stably related to better EF across a longer period of time. Such findings about stability across multiple ambulatory assessment data collection waves substantially expand the previous scientific literature.

Findings from *Study 1* of *Manuscript 2* suggest that the association between PA and EF not only varies between different time scales (*Study 2*) but also between different age groups. Here, we examined objectively measured PA and EF in a sample of 249 participants from different age groups (68 children, 144 adults, 36 older adults). Everyday PA was measured with accelerometers for seven days, and to assess EF, we implemented the same verbal fluency task in all age groups (Delis et al., 2001). Averaged across the age groups, we observed no association between MVPA and EF. This was unexpected, as previous research suggests a positive link between PA and EF across the life span (Colcombe & Kramer, 2003; Cox et al., 2016; Donnelly et al., 2016). Interestingly, when differentiating between age groups, we observed only a positive association in older adults. In children and adults, we found no association between PA and EF. In line with previous literature (Ludyga et al., 2016), our findings suggest that the link between PA and EF is strongest in older adults. However, Ludyga et al. (2016) also suggested that preadolescents might be specifically sensitive to PA-related

effects on EF. Since the age range of children in *Study 1* of *Manuscript 2* was rather broad (7-17 yrs) and the sample sizes to further differentiate between age groups in youth were too small, we did not specifically investigate the association between PA and EF in different age groups in youth. Possibly, and in line with the investigation across all age groups that revealed no relation, averaging across the wide age range in youth may have resulted in no relation, although it may have differed between age groups in youth. This highlights the necessity to differentiate between age groups when investigating the association between PA and EF in childhood and youth. Yet, the novel approach of implementing analogous measures for PA and EF in various age groups in *Study 1* of *Manuscript 2* to increase the comparability between research findings across the life span – as well as across different age groups in childhood and youth – is very promising to enhance our understanding of the association between PA and EF.

In summary, *Manuscript 2* augments our scientific understanding of the relation between everyday PA and EF in older children (a) through the implementation of an intensive longitudinal measurement burst design in *Study 2*, which allows (b) the examination of short-term within-person effect, (c) the differentiation between different times of day, as well as (d) to examine the stability of the effects across a longer period. Beyond that, *Study 1* of *Manuscript 2* enhances our scientific understanding by (e) examining the relation between everyday PA and EF in different age groups across the life span with comparable measures.

5.1.3. Main Results of Manuscript 3: Everyday Physical Activity and Well-Being in Adolescents

Given the numerous advantages of ambulatory assessment in scientific research, we also implemented an ambulatory assessment study in *Manuscript 3* to investigate the association between everyday PA and well-being in adolescents. In daily evening questionnaires, 125 adolescents reported on their daily PA as well as other daily behaviors impacted by the COVID-19 pandemic (i.e., screen time, social contacts) and their well-being for 28 consecutive days. Understanding how everyday PA and other daily behaviors are related to well-being is especially important in adolescence, since adolescents represent an age group at specifically high risk for the onset of internalizing disorders (Rapee et al., 2019). In the questionnaire employed in this study, as a measure of everyday PA, we summarized the self-reported time adolescents spent in PA (i.e., walking, cycling) and in sport activities in different contexts (i.e., leisure time, school, sports clubs). We found a between- as well as a within-person association between everyday PA and adolescent well-being (see *Figure 2*). Accordingly, adolescents who reported higher PA levels overall also reported higher well-being across the course of the study

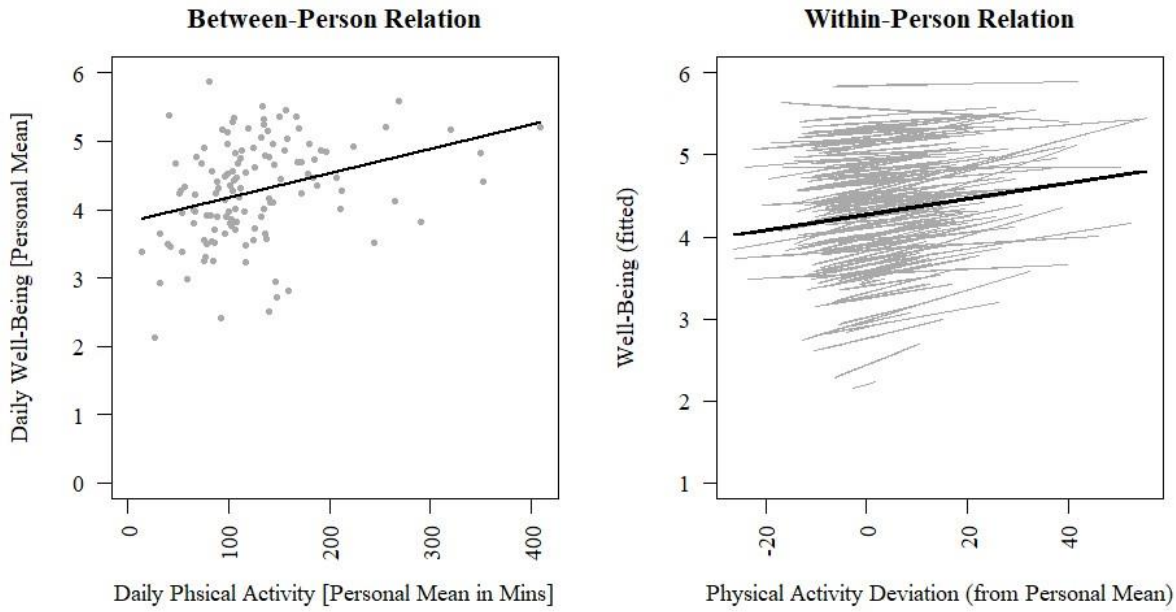
(between-person). This is in line with previous scientific findings suggesting that PA can be beneficial for adolescent well-being (Buecker et al., 2021; Kirkcaldy et al., 2002; McMahon et al., 2017) and mental health (Biddle et al., 2019; Brown et al., 2013; Oberste et al., 2020; Radovic et al., 2017; Rodriguez-Ayllon et al., 2019; Schuch et al., 2016). But in addition, the positive within-person association expands these previous findings: We observed that on days on which adolescents reported more PA than usual, they also reported higher well-being in the evening. Importantly, this finding suggests that it is not just important to be generally physically active, but instead *every day matters*. That is, even by increasing their PA levels on single days, adolescents can already promote their well-being. This complements findings from ambulatory assessment studies reporting positive within-person associations between everyday PA and adolescents' quality of life (Bourke et al., 2022) as well as positive affect (Bourke et al., 2021; Dunton et al., 2014). While these constructs are closely related to well-being, to my best knowledge, no other ambulatory assessment study has yet particularly examined the relation between everyday PA and adolescent well-being. Thus, findings from *Manuscript 3* not only support previous results from cross-sectional and longitudinal studies found on the between-person level, but they expand them through novel insight into short-term within-person links between everyday PA and well-being on the daily level.

Moreover, *Manuscript 3* differentiated between PA and sport activity in different contexts. Everyday PA consists of many different types of PA, which can be more or less structured and take place in various different (social) contexts. The conceptual model of mechanisms linking PA and psychological correlates like well-being (see *Figure 1*; Lubans et al., 2016), for example, suggests social connectedness as a possible psychosocial mechanism. Social connectedness can vary across different PA contexts, with individuals performing team sports in a sports club experiencing a stronger social connectedness and belonging, which can be especially beneficial for adolescent well-being (Doré et al., 2016; Eime et al., 2013; Sabiston et al., 2016). Accordingly, first evidence suggested that sports club participation during the pandemic was positively related to well-being (Basterfield et al., 2022). However, studies jointly examining different PA contexts and their effect on adolescent well-being are scarce. In our sample, we observed that besides PA (i.e., walking and cycling), sport activity in leisure time as well as sport activity in sports clubs was positively related to well-being within individuals. Thus, on days with either more PA, more sport activity in leisure time, or more sport activity in sports clubs, adolescents reported better well-being in the evening. Interestingly, no within-person association was evident for sport activity in school. Previous work suggests that the school context might be especially well-suited for positive PA-related

effects on adolescent well-being, since a wide range of students regardless of SES or other PA participation can be reached in schools (Cataldi et al., 2021; van Sluijs et al., 2021). However, our findings do not support this, as positive associations could only be observed for leisure time and sports club. Instead, since sport activity in schools is not voluntary, it might be related to a higher variability in motivation (Bagøien et al., 2010) compared to sport activity in leisure time and sport club, which adolescents can choose more freely and voluntarily. This might possibly explain why sport activity in schools was not positively related to adolescent well-being in our sample. Further, previous research suggests that the quality and content of PA offers in the school context can be crucial for effects on PA levels and enjoyment (Lubans et al., 2017), which we did not control for in our study. Including this in future investigations might lead to a better and more detailed understanding of the role of PA in the school context.

Figure 2

Relation Between Physical Activity and Well-Being Between Individuals (Left) and Within Individuals (Right) Observed in *Manuscript 3*



Note. The left panel displays the between-person relation between physical activity and well-being, revealing that adolescents reporting more physical activity than others also report higher well-being. The right panel displays the within-person association between daily physical activity and well-being, revealing that on days that individuals report to engage in more physical activity than usual, they report higher well-being. Here, the black line represents the within-person relation between physical activity and well-being averaged across all participants, and the gray lines represent the individual within-person relations for every participant.

In *Manuscript 3*, we not only focused on everyday PA and its role for adolescent well-being, but we also investigated other daily behaviors that were strongly affected by pandemic-related restrictions during the COVID-19 pandemic. As a consequence of restrictions and social isolation measures, the number of social contacts in youth decreased (Vogel et al., 2021) and increases in screen time were reported globally (Kharel et al., 2022). Evidence repeatedly suggests a negative link between pandemic-related increased screen time and adolescent well-being (Nagata et al., 2022). However, to my best knowledge, no previous ambulatory assessment study has jointly examined the interplay between PA, social contacts, and screen time, as well as their relation to adolescent well-being during the COVID-19 pandemic. Previous research suggests that PA and screen time are distinctly and independently related to mental health in youth and should be separately addressed in scientific investigations (Nigg et al., 2021; Page et al., 2010). In line with this, we found no interrelations between the different daily behaviors. Thus, the relation between PA and well-being was independent from adolescents' social contacts or screen time, and the effect of these daily behaviors was also independent of the reported PA levels: Social contacts were positively related to well-being within but not between individuals, as adolescents reported higher well-being on days with more social contacts than usual. Further, screen time was negatively related to well-being on both levels. Adolescents who reported more screen time overall reported lower well-being, and this could also be observed within individuals on the daily level. These findings suggest that PA is important for adolescents' well-being regardless of other daily behaviors, but including other behaviors in ambulatory assessment allows a better understanding of adolescents' daily lives.

Hence, the findings from *Manuscript 3* expand our understanding of the relationship between everyday PA and well-being in adolescents (a) within the context of the COVID-19 pandemic, (b) by specifically investigating short-term within-person processes, (c) by differentiating between various PA contexts (i.e., leisure time, school, sports club), and (d) by examining PA not independently but in combination with other daily behaviors, namely social contacts and screen time.

5.2. Methodological Considerations in the Measurement of Everyday Physical Activity

After summarizing and discussing the main results of the presented manuscripts with regard to the main research questions introduced in chapter *3. Research Aims*, I will now focus on some important methodological facets regarding the measurement of everyday PA: (1) differences between the implemented measurement methods (i.e., subjective vs. objective),

and (2) methodological aspects of ambulatory assessment. More precisely, I will expand the model of mechanisms presented in *Figure 1* (Lubans et al., 2016) through the advanced possibilities of ambulatory assessment, incorporating findings from the manuscripts in this dissertation.

5.2.1. Subjective and Objective Measurement of Everyday Physical Activity

In *Manuscript 1*, besides implementing an accelerometer as an objective measure of preschoolers' everyday PA for seven consecutive days, we also used a parental questionnaire (Bayer et al., 2012) to subjectively measure PA. For preschool-age, the number of reliable parental questionnaires to measure everyday PA is very limited (Hidding et al., 2018), and the questionnaires differ strongly. The questionnaire employed in *Manuscript 1* consists of seven items, measuring different aspects of children's typical PA. Parents are instructed to rate how often their child performs five different types of PA (e.g., play with a ball, play tag, ride a bike or scooter) in a typical week, ranging from *never* to *every day* on a five-point Likert-scale. Additionally, parents indicate with one item how often their child takes part in a sports club (5-point Likert-scale, *never* to *more than 2 hrs/week*), and with another item they specify how often their child goes to a public pool (5-point Likert-scale, *never* to *frequently*). Answers to all items are then defined as high (+1) or low frequency (-1). In the original study validating the questionnaire in a sample of 748 German preschoolers, participants were classified as showing low (-7 to -3), medium (-2 to 2) or high (3 to 7) PA levels based on the sum score, and this classification correlated with accelerometer-assessed MVPA and sedentary behavior (Bayer et al., 2012). Further, the classification was related to overweight status and performance in a motor test (Bayer et al., 2009). Accordingly, the authors argued that the questionnaire presents a valid measure, sufficiently reflecting different PA intensities in preschool-age.

To avoid categorization and loss of information and variance, in *Manuscript 1*, we used the sum score of all answers as a continuous measure of PA, as suggested in previous work with this questionnaire (Haas et al., 2022). Haas et al. reported that the sum score followed a normal distribution in a sample of 103 German preschoolers, and results did not change compared to the originally suggested classification (Bayer et al., 2012). In line with previous findings (Haas et al., 2022), the sum score was normally distributed in our sample. However, contradicting findings from the original validation study (Bayer et al., 2012), in our sample, the sum score of parent-reported PA was neither significantly related to time spent in accelerometer-measured MVPA nor light PA or sedentary behavior. This result pattern is in line with numerous previous findings showing differences between questionnaire- and accelerometer-assessed PA levels

across the lifespan (Adamo et al., 2009; Prince et al., 2008). Hence, our findings further support the understanding that subjective and objective PA measures should not be used interchangeably (Adamo et al., 2009; Prince et al., 2008; Toplak et al., 2013), and that the specific implemented measures should be considered when comparing scientific findings.

Different explanations are possible as to why the subjectively and objectively assessed PA levels differed in *Manuscript 1*. Regarding the parental questionnaire, the authors interpreted the outcome as a valid measure of PA (Bayer et al., 2012), whereas Haas et al. (2022) suggested that it rather measured children's previous motor coordination experience. I would also argue that the questionnaire assesses a specific component of PA that cannot without restrictions be interpreted as a measure of everyday PA, since it only measures a very limited number of types of PA performed by preschoolers. Objectively measured PA, on the other hand, includes a wider variety of PA exhibited by preschoolers in their everyday life, possibly explaining the inconsistency between the two implemented PA measures in *Manuscript 1*. Yet, it should be noted that accelerometers do not capture all types of PA performed in everyday life, as they cannot be worn during water sports or high impact sports (e.g., karate). In direct contrast, the parental questionnaire (Bayer et al., 2012) specifically assesses how often children go to a public pool. Further, accelerometers only detect accelerations of the body, neglecting strengthening exercises like yoga, and the measured accelerations depend on the wearing location of the accelerometer. In *Manuscript 1* accelerometers were worn on the hip, thus, body movements of the upper body could not be detected. These limitations directly affect the comparability between subjective and objective measures of PA, as also seen in our findings.

Thus, as stated in the pre-registration for *Manuscript 1* in case of limited correlation between the implemented subjective and objective PA measurement methods (see: https://osf.io/v9fc4/?view_only=bfab58215c314f97a7271abe1bcbc774), we focused on the accelerometer-assessed time spent in MVPA as the central measure of interest for PA. Still, we also examined the association between parent-reported PA and preschoolers' EF performance in the EF Touch, which was not significant. Thus, the association between PA and EF differed depending on the implemented PA measurement method, as only accelerometer-assessed MVPA was negatively related to EF, but no association was evident with parent-reported PA. This result pattern further strengthens our understanding that different measurement methods of PA are not directly comparable (Adamo et al., 2009; Prince et al., 2008; Toplak et al., 2013), and expands this by showing that the relation between PA and EF directly depends on the applied measurement method. This should therefore not only be considered in the interpretation and comparison of prior research findings but also in the planning of future investigations.

5.2.2. Ambulatory Assessment in the Measurement of Everyday Physical Activity

Another important methodological consideration in the investigation of everyday PA concerns the study design. Besides deciding *how* to measure everyday PA, the question arises *how often* PA – and its potential correlates – should be measured in everyday life to capture their variability and to understand associations on smaller time scales. Ambulatory Assessment can lead to a better understanding of antecedents (e.g., affect predicting PA) and consequences of PA (e.g., PA predicting affect) in *real-time* and *real-life*, which can yield theoretical and practical implications for the maintenance and promotion of PA in youth (Dunton et al., 2014). Objective PA measurement methods like the accelerometer typically represent a form of ambulatory assessment, as PA is continuously monitored within participants' everyday lives. To examine potential antecedents and consequences of PA, it is important to also measure these psychological correlates repeatedly (e.g., repeated spatial working memory task in *Study 2* of *Manuscript 2*; Dirk & Schmiedek, 2016; Galeano Weber et al., 2018).

Ambulatory assessment can (1) depict the *within-person variability* of everyday PA and its psychological correlates in a naturalistic and ecologically valid environment, (2) enable the examination of associations not only between individuals but also *short-term within-person associations* on different time scales, as well as (3) allow the examination of *cross-level associations*, namely between-person differences in within-person associations. Further, (4) ambulatory assessment permits the examination of *bidirectional associations* through repeated measurement (Russell & Gajos, 2020). Hence, findings from ambulatory assessment studies can improve our understanding of the relation between everyday PA and psychological correlates in youth and expand the knowledge about the linking mechanisms.

In *Figure 3*, I adapted and expanded the conceptual model of mechanisms linking PA and psychological correlates suggested by Lubans et al. (2016; see *Figure 1*). All theories about the relation between everyday PA and psychological correlates inherently assume a within-person association (e.g., Best, 2010; Diamond, 2012; Lubans et al., 2016). However, most research designs examining the association rely on between-person comparisons, although within-person relations can substantially differ from associations observed on the between-person level (Schmiedek et al., 2020). In addition, the suggested linking mechanisms can also be assigned to the between-person level (e.g., different PA types performed by different individuals) or the within-person level (e.g., physical feeling states which vary within individuals over time). I visualize these two aspects in *Figure 3* by including the two levels (between-person, within-person) to the conceptual model previously presented in *Figure 1*

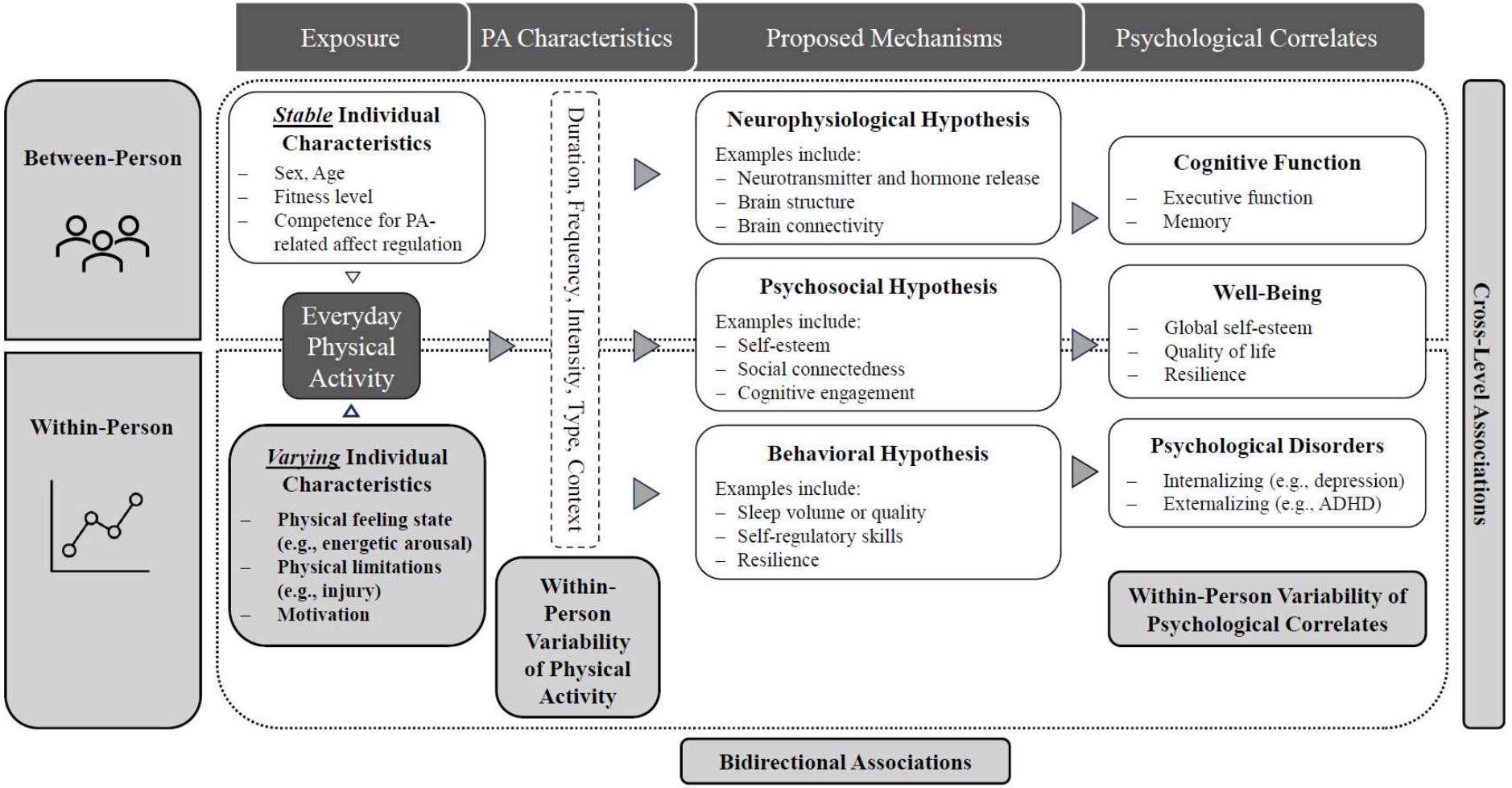
(Lubans et al., 2016). Further, I complement the model with aspects of the relation between everyday PA and psychological correlates that can exclusively be examined with ambulatory assessment studies (e.g., cross-level associations; Russell & Gajos, 2020). In the following paragraphs, I will explain and discuss these aspects as well as the changes in *Figure 3* compared to *Figure 1* in more detail.

First, in this dissertation, we observed *within-person variability of PA* in youth's everyday lives (see *Figure 3*), with PA fluctuating across seasons and within the same day in *Manuscript 2* as well as across days in *Manuscript 3*. Thus, to better understand the role of everyday PA, this within-person variability needs to be considered in scientific research, and ambulatory assessment is especially well-suited for this goal. The objective monitoring of PA within individuals' everyday lives is a very promising method for this (Reichert et al., 2020), implemented in *Manuscript 1* and *Manuscript 2* of this dissertation. But questionnaires can also be adapted to assess PA on different time scales – for example, on the daily level (e.g., 'How much time did you spent in PA today?') or on smaller time scales (e.g., 'In the last two hours, how much time were you physically active?'), and they can inform about different facets of objectively measured PA like the context, which was assessed in *Manuscript 3*.

Further, *within-person variability of psychological correlates* (see *Figure 3*) has also been repeatedly reported for EF (Dirk & Schmiedek, 2016; Galeano Weber et al., 2018; McKinney et al., 2020) and well-being (De Vries et al., 2021), which was also supported by findings from *Manuscript 2* regarding EF and *Manuscript 3* regarding well-being. Through constant monitoring or repeated measurement, the real-life variability of everyday PA as well as psychological correlates can be depicted in real-time, allowing the examination of their relation in close timely proximity and with high ecological validity. Hence, as depicted in *Figure 3*, ambulatory assessment studies yield new information about the variability of PA as well as variability of psychological correlates, thereby granting new insight into the relationship between both on smaller time scales.

Figure 3

Extension of the Conceptual Model of Mechanisms Linking Physical Activity and Psychological Correlates Through Ambulatory Assessment



Note. Additions to the model suggested by Lubans et al. (2016; see *Figure 1*) are highlighted bold and presented in light grey boxes.

Second, ambulatory assessment studies allow to differentiate effects found on the between-person level from *short-term within-person associations* observed over time (within-person level depicted in *Figure 3*). Longitudinal study designs also allow the investigation of within-person associations over time, but because of a typically very limited number of assessments, conclusions about short-term associations are restricted (Bolger & Laurenceau, 2013). Instead, through temporally close consecutive measurements, short-term within-person associations can be examined in ambulatory assessment designs. Hereby, it is fundamentally important to consider (a) the time frame in which the constructs under examinations vary, and (b) the time frame in which a relation between the examined constructs is expected. That is, the study design needs to reflect the expected underlying *theory of change* explaining short-term within-person relations (Bolger & Laurenceau, 2013; Russell & Gajos, 2020). In line with the underlying theory of change, these within-person relations can be examined on different time scales, as presented in *Study 2* of *Manuscript 2*, where PA was continuously monitored with accelerometers and EF was assessed three times per day. This particular frequency of the repeated measurement allows the examination of three different time scales: the link between (a) PA in the morning and subsequent afternoon EF, (b) whole-day PA and subsequent evening EF, and (c) prior-day PA and EF in the next morning. However, more research employing ambulatory assessment is necessary to better understand the timing of the associations between PA and its psychological correlates as well as the underlying theory of change, which I will discuss more thoroughly in chapter *5.3. Limitations and Directions for Future Research*.

The differentiation of between- and within-person associations requires complex data analysis methods, and a number of different statistical methods has been developed in the past decades (Bolger & Laurenceau, 2013). Typically, in the statistical analysis, an individuals' mean is employed for the examination of between-person effects, and the deviation from an individuals' mean is typically determined to examine within-person associations. For example, in *Study 2* of *Manuscript 2*, for the evening analysis, we averaged across participants' time spent in MVPA during the entire study duration to examine the between-person level. To investigate within-person effects, we determined for each day how much an individual deviated from their personal average time spent in MVPA per day. This procedure allows the interpretation of findings on two levels: (1) on the between-person level, we can draw conclusions about the general relation between individuals' overall everyday PA levels amd psychological correlates like EF (*Manuscript 2*) or well-being (*Manuscript 3*), while (2) on the within-person level, we can interpret how more everyday PA than usual is related to an individuals' psychological correlates for example within the same day or on the subsequent day

(next morning EF in *Study 2* of *Manuscript 2*). Such short-term associations on the within-person level yield novel insight into the association between PA and psychological correlates in youth – above and beyond what is already known from between-person comparisons.

Findings from both ambulatory assessment studies presented in this dissertation (*Manuscript 2*, *Manuscript 3*) underline the importance of differentiating relations found between individuals from those found within individuals, as the effects differed depending on the examination level: In *Manuscript 2*, we only observed positive between-person associations between PA and EF, while the within-person associations were not significant. In *Manuscript 3*, we found similar results for PA and screen time between and within individuals, but regarding social contacts, we only observed a positive association with well-being within and not between individuals. Our findings highlight that ambulatory assessment is indispensable because cross-sectional examinations are insufficient to detect within-person associations. With psychological theories of associations between PA and its correlates inherently assuming associations within individuals, it is important to explicitly examine them in ambulatory assessment and distinguish them from the general associations observed on the between-person level. I emphasized the possibility of differences in between- and within-person associations by accentuating in *Figure 3* that the entire conceptual model linking everyday PA and psychological correlates (Lubans et al., 2016) can be differentiated into the between-person and the within-person level.

Third, and beyond the differentiation of between- and within-person associations, ambulatory assessment also permits to integrate both levels to examine *cross-level associations*, depicted as spanning both levels in *Figure 3*. Such a procedure allows the investigation of between-person variability in within-person associations, which can statistically be accounted for by including random effects in multilevel models, as illustrated with findings from *Manuscript 3*: Here, we found a significant random effect of PA, suggesting variance in the within-person association between PA and well-being. Thus, while averaged across all participants, we found a positive within-person association on the daily level, this association significantly differed between individuals in its strength, with some within-person associations even being negative (see *Figure 2*).

Such between-person variability in within-person associations could be explained through *process-by-person* or *process-by-context* interactions (Russell & Gajos, 2020). Previous research examining possible cross-level moderations suggests that the within-person relation between everyday PA and psychological correlates depends on individual characteristics (process-by-person) as well as social or contextual factors (process-by-context).

Regarding the moderating role of individual characteristics, evidence from an adult sample suggests that the individual competence for PA-related affect regulation moderates the association between PA and affect in everyday life (see *Figure 3*; Sudeck et al., 2018): Individuals with high competence felt more calm after PA, while individuals with low competence felt more calm and relaxed during periods of sedentary behavior. To pick up the example from the introduction of a toddler learning how to walk, the toddlers motor developmental stage represents a between-person individual characteristic that moderates the within-person association between speed of walking and risk of falling: Toddlers with higher developed motor skills might be less likely to fall when walking or running at the same speed as toddlers with lower levels of motor development. Regarding the cross-level moderation of contextual factors, an ambulatory assessment study with adolescents suggested that social interactions with peers moderated the link between the perceived safety of the neighborhood and adolescents' everyday PA, with neighborhood safety only predicting PA in adolescents with less social contacts (Salvy et al., 2017). Such cross-level interactions can possibly explain inconsistencies in the link between PA and psychological correlates reported in prior studies, and they can best be examined with ambulatory assessment (Russell & Gajos, 2020).

Fourth, ambulatory assessment studies allow to examine *bidirectional associations* (see *Figure 3*) between everyday PA and psychological correlates. Typically, directionality and causality are investigated in experimental study designs implementing PA interventions. Given the limited transferability of results from such studies to everyday PA, examining the directionality of relations with ambulatory assessment presents a unique opportunity. Because of the repeated measurement, the obtained data presents a sequence that allows to examine directionality in observational study designs in individuals' naturalistic environment. The within-person examination in ambulatory assessment further facilitates the interference of causality: In the statistical analysis of ambulatory assessment, individuals can serve as their own 'control' with stable individual characteristics (e.g., age, gender), as deviations are compared to the individual mean (Russell & Gajos, 2020). Most importantly, not only previously defined variables are controlled for, but also unmeasured variables are constant within individuals (e.g., competences, attitudes) and, thus, automatically controlled for in the investigation of within-person associations. This allows the thorough examination of antecedents as well as consequences of everyday PA, but the investigation of causality is nevertheless limited (see chapter *5.3. Limitations and Directions for Future Research*).

In the ambulatory studies presented in this dissertation, we focused on consequences of everyday PA, since we assessed (a) PA in time windows of varying length and subsequent EF

performance in *Manuscript 2*, and (b) PA across the entire day and well-being in the subsequent evening in *Manuscript 3*. However, findings from previous ambulatory assessment studies suggest bidirectional associations between youth's everyday PA and sleep (Master et al., 2019), happiness (van Woudenberg et al., 2020), and affective states (Dunton et al., 2014). For example, feeling more energetic and less tired was related to preadolescents spending more time in MVPA in the following 30 minutes, and more MVPA in the 30 minutes prior was related to more positive affect and feeling more energetic (Dunton et al., 2014). Findings like this yield first insights into (bi-)directional associations in youth's everyday lives. However, as mentioned above, the alignment between the repeated measurement occasions and the time frame of the association with its underlying theory of change is a challenge in the examination of bidirectionality that should be considered in the planning of ambulatory assessment studies: Associations could for example be missed or overlooked if measurement occasions are too far apart (Bolger & Laurenceau, 2013; Russell & Gajos, 2020).

5.3. Limitations and Directions for Future Research

Despite the numerous advantages of the manuscripts presented in this dissertation and the indisputable novelty of the presented findings, more research is necessary to better understand the link between everyday PA and psychological correlates in childhood and youth. In the discussion, I already mentioned some suggestions for future directions, like the examination of bidirectional relations in ambulatory assessment, which I will present in more detail in this chapter of the discussion. Further suggestions for future research can be derived from limitations of the presented research. These limitations concern (1) the *implemented measures*, (2) the *implemented study designs*, as well as (3) the restricted possibility to investigate *causal links and mechanisms* in this dissertation. Lastly, I argue that previous research might profit from a shift of focus away from merely focusing on everyday PA, and instead integrate it with other behaviors exhibited in everyday life, as an approach to capture the *24-Hour Activity Cycle* individuals undergo daily.

First, there were some limitations concerning the *implemented measures* of everyday PA as well as its correlates EF and well-being implemented in this dissertation, and I want to highlight three different aspects: limitations (a) in measurement methods for ambulatory assessment, (b) regarding the comparability between measurement methods implemented in this dissertation, and (c) in the integration of multiple characteristics of PA (e.g., intensity, context, type).

Despite an increasing interest in ambulatory assessment (Russell & Gajos, 2020) as well as related technological advances for the investigation of PA in everyday life (Reichert et al., 2020), (a) there is still only a limited number of questionnaires or tests available for ambulatory assessment with children or adolescents. For example, so far, there is still limited research on properties of ambulatory cognitive assessment, and no normative data is available (Moore et al., 2017). The working memory task employed as an EF measure in *Study 2* of *Manuscript 2* was previously developed and validated in older children (Galeano Weber et al., 2018; Könen et al., 2016). Yet, we observed a ceiling effect in the easier task condition in our sample that was only slightly older than the sample in the original validation study. This supports the notion that more reliable and valid measurement methods need to be developed for ambulatory assessment in children and adolescents, and their age-specific applicability needs to be confirmed because of fast developmental changes in childhood and youth.

Another important limitation regarding the measurement methods for ambulatory assessment in this dissertation was that in *Manuscript 3* we implemented adapted questionnaires to assess PA, screen time, as well as well-being, and self-developed questions to assess social contacts. This was due to the limited availability of previously validated questionnaires for ambulatory assessment in youth. Standardized questionnaires from other study designs are not feasible for repeated measurement because of the wording or the length of the questionnaires (Trull & Ebner-Priemer, 2013), so they need to be re-phrased or shortened for the implementation in ambulatory assessment (Reichert et al., 2020). Such adaptations can compromise the psychometric properties of pre-exiting scales developed for one-time assessments. Hence, more research is necessary to develop reliable and valid subjective and objective measurement methods for ambulatory assessment in childhood and youth.

Further, another limitation concerning the measurement methods of ambulatory assessment refers to the statistical analysis of the accelerometer data from *Study 2* of *Manuscript 2*: One of the major advantages of ambulatory assessment is that such study designs can capture the variability of daily behaviors like PA. However, if PA is then averaged across longer periods of time like in *Study 2* of *Manuscript 2*, valuable information about the occurring variability is lost. Instead, future work examining everyday PA in ambulatory assessment could take this variability into account by investigating activity rest patterns (Migueles et al., 2021) or PA in smaller time frames (e.g., Dunton et al., 2014; Trevillion et al., 2022). For *Study 2* of *Manuscript 2*, the original analysis plan included an additional analysis of the relation between PA exhibited in smaller time windows (e.g., 10 mins, 20 mins) directly before EF assessment. Because of the already extensive complexity of *Manuscript 2*, this analysis was not yet

conducted but should be performed in next steps. Given that our analysis revealed no within-person associations between PA and EF in the examined time frames, an investigation of varying time frames before the EF assessment could yield important information about the time scale on which such within-person associations occur (Russell & Gajos, 2020).

Another methodological limitation concerns (b) the comparability of measurement methods of everyday PA implemented in this dissertation. As pointed out in the chapter *2.2.1. Subjective and Objective Measurement Methods*, the comparability between subjective and objective PA measures is limited (Adamo et al., 2009; Prince et al., 2008), and differences between the measurement methods can influence the observed relation to psychological correlates (*Manuscript 1*). In this dissertation, the PA measurement methods differed between the manuscripts, with everyday PA being assessed only through self-report in *Manuscript 3* and only through accelerometer in *Manuscript 2*. Solely *Manuscript 1* compared subjective (i.e., parental questionnaire) and objective measurement methods (i.e., accelerometer) of everyday PA, suggesting strong differences and a limited comparability. Besides the chosen measurement method, the applied data analysis approach also limits the comparability: Within the manuscripts in this dissertation objectively assessing PA with an accelerometer, we applied different cut-points to define PA intensities. An overview of the applied cut-points in this dissertation is presented in *Table 1*. Differences between *Manuscript 1* (preschool) and *Manuscript 2* (older children) are justifiable because of the different ages of the investigated samples. However, cut-points can also vastly differ within the same age groups (Migueles et al., 2017; Trost et al., 2011; van Cauwenberghe et al., 2011), and in *Manuscript 2*, we applied different cut-points for comparable age groups: In *Study 1*, we investigated different age groups across the lifespan (i.e., children, adults, older adults), and we applied the cut-point defined by Freedson et al. (2005) for children to be more consistent with the cut-points applied for adults (Freedson et al., 1998). In *Study 2*, we implemented the cut-points suggested by Evenson et al. (2008) instead, because they show a high accuracy when measuring PA on the vertical axis of hip-mounted accelerometers and are recommended as the most appropriate cut-points for youth (Migueles et al., 2017). Further, the classification accuracy is acceptable across all intensity levels over a wide age range in youth (5-15 yrs; Trost et al., 2011). When re-analyzing the data from *Study 1* using the cut-points applied in *Study 2* (Evenson et al., 2008), the results were similar. Still, for better comparability, it is important that homogeneous standards for the measurement of everyday PA are developed and consistently applied in future research.

Another methodological limitation regarding the measurement of everyday PA in this dissertation concerns (c) the integration of multiple characteristics of PA. As suggested in the

conceptual model linking PA and psychological correlates (see *Figure 1*; Lubans et al., 2016), multiple PA characteristics influence the relation (e.g., duration, intensity, type, context). In this dissertation, we only integrated two separate characteristics of PA in *Manuscript 3*, namely *duration* and *context of PA*. This revealed differences in the association between PA duration and well-being depending on the specific context (i.e., leisure time, school, sports club), suggesting that considering the context of PA is of central importance to better understand its role for psychological correlates. Other work has also suggested that PA performed outdoors and in nature-based environments is especially beneficial for well-being (Korpela et al., 2014). In addition, an important characteristic that should be considered is the *type of PA*. Previous theoretical work has suggested that cognitively engaging PA like yoga or team sports might be more beneficial for EF and its development (Best, 2010; Diamond, 2012). Empirical evidence from experimental studies is mixed, but yields some support for this hypothesis regarding PA interventions (de Greeff et al., 2018). To better understand the interplay between different characteristics of everyday PA, it is important that future work integrates multiple PA characteristics also in observational studies (e.g., intensity and context; duration and type). With technological advances, devices have been developed that can objectively measure and distinguish between types of PA, as for example the Fitbit (Fitbit Inc, San Francisco, CA, USA). However, they tend to overestimate the time spent in high intensity PA compared to accelerometers (Feehan et al., 2018), and the combination of subjective methods assessing qualitative aspects of PA with objective methods assessing quantitative aspects of PA is still particularly promising. For example, objectively measured PA or inactivity could then trigger a subjective assessment of type of PA or other characteristics that cannot otherwise be examined (e.g., motivation).

Second, regarding the *implemented study designs* in this dissertation, (a) I will focus on limitations in the comparability of measurement duration and frequency, and (b) I will specifically emphasize limitations in the ambulatory assessment study designs in *Manuscript 2* and *Manuscript 3*. One limitation of the implemented study designs directly affecting the comparability of the manuscripts presented in this dissertation concerns (a) the measurement duration and frequency of the assessed constructs. In *Manuscript 1*, we measured preschoolers' everyday PA continuously with an accelerometer for seven days, while EF was only measured once with a performance-based test in a highly structured and standardized setting. The measurement of PA and EF in *Study 1* of *Manuscript 2* was comparable. In *Study 2* of *Manuscript 2*, we also continuously monitored preadolescent's everyday PA with accelerometers for three 18-day data collection waves. In contrast to *Manuscript 1* and *Study 1*

of *Manuscript 2*, we assessed preadolescents' EF repeatedly three times per day with a short task in their naturalistic surrounding. In contrast *Manuscript 3*, we assessed PA and well-being once per day in the evening through self-report. These differences in the study designs restrict the comparability between the results presented in this dissertation, but they provide different insights into the relation between everyday PA and its psychological correlates.

Regarding *Manuscript 1*, the measurement duration and frequency of PA and EF directly determine the assessed aspects of the constructs. On the one hand, the accelerometer-assessed PA depicts PA levels within preschoolers' naturalistic environment. In contrast, EF was objectively measured with an extensive test battery, with a highly standardized test administration and the one-on-one test situation taking place in a separate and quite room with limited distractions. Hence, preschoolers' EF were not assessed in a naturalistic environment, and the EF measured with the EF Touch rather represent preschoolers' EF capacity in situations with high external motivation (Toplak et al., 2013). The difference between the context of PA and EF assessment needs to be considered when interpreting the results from *Manuscript 1*. It is likely that a child displaying EF dysfunctions in everyday life might compensate these problems and perform adequately in an EF test battery in a well-structured setting with reduced distractions. Examining the relation between everyday PA and EF in a naturalistic environment might yield distinct and important insights into the relation between PA and EF. For this, future research could specifically focus on measuring preschoolers' EF in their daily life – either by creating a less artificial test situation and possibly repeatedly measure EF or through observation in their natural environment (e.g., with video recording). So far, the number of reliable and valid EF measurement methods for preschool-age is very limited, and their applicability for ambulatory assessment has not been examined previously. One previous ambulatory assessment study repeatedly assessed parental reported self-regulatory skills related to EF (Ludwig & Rauch, 2018), but more research with preschoolers is necessary to investigate the applicability and feasibility of ambulatory cognitive assessment under consideration of the participant burden within this young age group.

Concerning the duration and frequency of measurement in older age groups in youth, some previous research with adolescents suggests associations between PA and mood within the same day (Bourke et al., 2021). That is, the correspondent theory of change expects a link between PA and mood within the same day. Our findings from *Manuscript 3* support this also for well-being. As emphasized previously in chapter *5.2.2. Ambulatory Assessment in the Measurement of Everyday Physical Activity*, the underlying theory of change is of central importance for the planning of a study design examining everyday PA (Bolger & Laurenceau,

2013; Russell & Gajos, 2020). Regarding the short-term within-person association between everyday PA and EF, however, the body of research is very limited, and the underlying timing of the relationship is not yet definite: Trevillion et al. (2022) only found a within-person link between prior day PA and EF in the subsequent morning, but not for PA in the two hours prior to the EF assessment. This suggests that the association between PA and EF in preadolescents is time sensitive and cannot be observed on all time scales, but there is no evidence concerning other time scales. *Study 2* of *Manuscript 2* presents the first ambulatory assessment study to examine other time scales: We also found differences in the between-person relation depending on the time of day but interestingly found no within-person relation on any time scale and at any time of day. However, I want to emphasize this should not be interpreted as there not being a within-person link between PA and EF in preadolescents. Instead, I argue that more research is necessary to understand at what time of day and on what time scale this association is evident. For example, examining the association between PA after school hours and subsequent EF in the evening could be especially interesting, as PA after school hours is likely to vary more strongly between as well as within individuals than PA during school hours. Alternatively, investigating the association between PA during school hours on EF exhibited in school could inform researchers about the association within the educational setting, in which EF can be especially important. For this, future research could implement the working memory task used in *Study 2* of *Manuscript 2* (Dirk & Schmiedek, 2017; Galeano Weber et al., 2018), as it can easily be integrated into the school day with its short duration. Findings from ambulatory assessment could inform researchers about the underlying theory of change regarding PA and EF in childhood and youth, enabling timely interventions (see chapter *5.4. Practical Implications*).

Regarding (b) the ambulatory assessment studies presented in this dissertation, it is important to consider that the repeated measurement of psychological correlates in everyday life might lead to changes in the measured variables – not only through the possibility of measurement reactivity, but also through training effects or the repeated measurement functioning as an ‘unplanned intervention’. In *Study 2* of *Manuscript 2*, we observed that participants’ EF performance in the spatial working memory task was significantly higher in the second and third data collection wave compared to the first. This suggests some training effects in the EF task. Interestingly, within the data collection waves, we did not find a significant increase across the 18 days of data collection. Thus, the training effect was not evident from day-to-day within the data collection waves, but participants might have isntead profited from previously participating in another data collection wave. In line with this,

participants that were newly recruited for the second data collection wave performed worse in the second data collection wave compared to preadolescents that had already participated in the first, but the difference was not significant. In *Manuscript 3*, we observed a significant increase in well-being across the study duration. Some Participants indicated in an open question at the end of the daily questionnaires that the daily questionnaires helped them in their daily reflections, suggesting that the questionnaires might have functioned as an 'unplanned intervention'. Previous studies have shown that reflecting on the daily occurrences can aid individuals' well-being (Kim & Kang, 2022; Newman & Nezlek, 2019). Hence, such effects need to be considered in the interpretation of findings from ambulatory assessment studies.

Third, I want to point out the limited possibility to investigate *causal relations and linking mechanisms* between everyday PA and psychological correlates in this dissertation. Experimental study designs – ideally, randomized controlled trials – are the golden standard to examine causal relations in psychological science. However, as emphasized before, findings from experimental studies investigating PA interventions are not necessarily transferrable to individuals' everyday PA. It is important to consider that study design (i.e., experimental vs. observational) and mode of examining PA (i.e., PA intervention vs. everyday PA) are inevitably confounded, and novel techniques for the investigation of causality in everyday life and with high ecological validity need to be developed and implemented. While it is indisputable that cross-sectional observational study designs like the one implemented in *Manuscript 1* are not adequate for the investigation of causality and directionality of associations, ambulatory assessment studies to some degree allow such investigations within individuals' naturalistic environment with the possibility of examining cross-level interactions.

Previous research has already suggested bidirectional associations between PA and EF (e.g., Daly et al., 2015) but also PA and affect (Dunton et al., 2014; van Woudenberg et al., 2020). Although this dissertation focuses on everyday PA as a precursor, as suggested by the conceptual model of linking mechanisms (see *Figure 1*; Lubans et al., 2016), the other effective direction can also be theoretically reinforced: For EF, it has been hypothesized that individuals with higher EF exhibit higher adherence to different health behaviors, like PA (Daly et al., 2015). With data from study designs like *Study 2* of *Manuscript 2*, it would be possible to also examine this direction. Instead of focusing on PA exhibited before the EF assessment, future analyses could focus on examining whether EF predicts subsequent PA levels in youth. Concerning the bidirectional association between PA and well-being or affect, it has been hypothesized that individuals should be more likely to continuously engage in PA over time after experiencing PA-related increases in well-being and affect (Liao et al., 2015). That is,

after repeatedly experiencing a 'runner's high', an individual is more likely to continuously go for runs – possibly, with the concrete goal of increasing their well-being. Future ambulatory assessment studies could focus on further examining such bidirectional associations, especially in youth samples (Russell & Gajos, 2020). In such work, an additional focal point could be to further examine linking mechanisms in everyday life (Biddle et al., 2019). De facto, I plan such an analysis in a next step with data used in *Manuscript 3*: To better understand the variability in the within-person relation between PA and adolescent well-being (see *Figure 2*), I plan to investigate individuals' competence for PA-related emotion regulation as a possible cross-level moderator, suggested by previous findings from an adult sample (Sudeck et al., 2018).

Lastly, I want to point out another perspective that should be considered in future research when investigating PA in individuals' everyday lives. In recent years, a new research paradigm has emerged within the field of health psychology, taking into account that daily activities like PA, sedentary behavior, and sleep are not independent from one another: the *24-Hour Activity Cycle* (Buman et al., 2014; Rosenberger et al., 2019). The 24-Hour Activity Cycle considers that daily behaviors are distributed across the whole day, and if more time is spent in one behavior, less time is disposable for other behaviors. Therefore, the 24-Hour Activity Cycle offers a new possibility for the investigation of the interrelatedness of health behaviors in ambulatory assessment, by examining the effect of *reallocation* of time spent in one activity (e.g., sedentary behavior) to time spent in another activity (e.g., PA). For example, reallocating as little as five minutes spent in sleep or light PA to time spent in MVPA was positively related to EF in preschoolers (Bezerra et al., 2020).

This interrelatedness of daily behaviors has also been considered in the *Canadian 24-Hour Movement Guidelines* for childhood and youth (aged 5-17 yrs; Tremblay et al., 2016) as well as for young children (aged 0-4 yrs; Tremblay et al., 2017), which have been adopted by other countries like Australia and New Zealand. According to these guidelines, children and adolescents should perform at least 60 minutes per day of MVPA (in line with the WHO guidelines), which should specifically incorporate muscle and bone strengthening activities three times per week, and several hours of light PA are recommended per day. Further nine to eleven hours of interrupted sleep per night are suggested for children aged five to 13 years (8-10 hours for 14- to 17-year-olds), and no more than two hours of recreational screen time per day are advised. Reviews and meta-analyses support that the adherence to these 24-hour guidelines is positively related to physiological and psychological health outcomes across the lifespan (Rollo et al., 2020), with high PA and sleep but low sedentary behavior representing the best combination in youth (Saunders et al., 2016). Yet, across the globe, the vast majority

of children and adolescents do not meet these guidelines (Tapia-Serrano et al., 2022). In *Manuscript 3*, we included different daily behaviors (i.e., PA, screen time, social contacts), and found that all were significantly and independently related to adolescent well-being. In an exploratory analysis expanding *Manuscript 2*, we also integrated sleep quality (i.e., 'How well did you sleep last night?') to examine its association to EF performance in the subsequent morning[1]. We observed a positive within-person association. Hence, after a night with better sleep than usual, individuals showed better EF in the morning. Including sleep quality did not influence the relation between PA and EF (i.e., no significant interaction), suggesting that PA and sleep were independently related to EF performance in the morning. Such findings yield first insight into the interrelatedness between different daily behaviors including PA and their relation to cognitive performance. But still, more research integrating different health behaviors and focusing on the 24-Hour Activity Cycle in youth samples is necessary to better understand the role of everyday PA within children's and adolescents' everyday lives.

5.4. Practical Implications

This dissertation focuses on the investigation of everyday PA and its association with psychological outcomes in children and adolescents. Reaching a better understanding of the relevance of PA in youth and how to possibly promote it within everyday life is important, because in the presented manuscripts only in the preschool sample (*Manuscript 1*) the majority met the WHO guidelines for PA. In preadolescence (*Manuscript 2*) and adolescence (*Manuscript 3*), the majority did not fulfill the WHO guidelines, supporting other recent findings from Germany (Bucksch et al., 2024). Remarkably, we only observed a negative association between everyday PA and EF in the preschool sample mostly fulfilling the WHO guidelines (*Manuscript 1*), while the associations between everyday PA and EF (*Manuscript 2*) as well as well-being (*Manuscript 3*) were positive in the older samples, which mostly did not fulfill the WHO guidelines. I want to emphasize that the negative association between everyday PA and EF observed in preschoolers should not be interpreted as a detrimental effect of PA (e.g., causality not examined, see *5.3. Limitations and Directions for Future Research*). Instead, it is a positive finding that preschoolers mostly met the WHO guidelines because young children are in an important motor development phase, which the recommended time of PA can aid. Promotion of PA in this age group could instead target sports club participation, as PA in this context could be more structured and possibly more beneficial for EF development (Best, 2010). Further, positive effects of sports club participation in preschool age have been reported

[1] Not included in the final *Manuscript 2*, because it did not significantly improve the prediction of EF.

for fitness level and body fat percentage (Ebenegger et al., 2012). Findings from *Manuscript 3* additionally underline the relevance of PA in sports clubs for adolescent well-being. Hence, sports club participation is important and should be promoted already in early years.

The promotion of PA appears very promising for public (mental) health because of its easy and wide applicability (Fegert et al., 2020). With decreasing PA levels across childhood and adolescence (van Sluijs et al., 2021) and the majority of youth not meeting recommended PA levels (Bucksch et al., 2024), everyday PA should be promoted as early as possible. Evidence suggests that the risk for depressive symptomatology in 18-year-olds is lowest in individuals with persistently high levels of MVPA (Kandola et al., 2020). That everyday PA was positively related to psychological correlates in the older samples of the presented manuscripts further underlines that the relevance of promoting everyday PA intensifies with increasing age. The promotion of a physically active lifestyle could be especially promising in adolescence, because individuals start to experience an increasing autonomy and develop lifestyle habits that can consolidate in later life stages (van Sluijs et al., 2021). In line with other findings (White et al., 2018), our findings from *Manuscript 3* suggest that it is especially important to promote PA in leisure-time and sports clubs, since PA in these contexts was positively related to well-being in adolescents.

Regarding PA promotion in youth, it is important to consider that different stakeholders might vary greatly in what they consider to be relevant: Policy makers and health professionals might be interested in reducing health-care costs and morbidity rates, while educators and parents might focus on academic achievement, and in contrast, more immediate outcomes like well-being, social connectedness, and enjoyment might be most relevant to children and adolescents (Williamson et al., 2020). Moreover, physical inactivity presents a complex problem, occurring within a complex social and environmental context (Rutter et al., 2019), which is also accounted for in the *Global Action Plan on Physical Activity 2018-2030* (World Health Organization, 2018), aiming to create environments that enable people and societies to be more active. Accordingly, van Sluijs et al. (2021) suggest that the following systems should be considered in the planning and implementing of PA promotion in youth: (a) the educational environment, (b) the social and digital environment, as well as (c) the living environment.

Regarding (a) the educational environment, school-based interventions promoting everyday PA can reach large populations, irrespective of SES or other individual characteristics. They have most often been examined in the literature of youth PA promotion and can foster PA literacy, which is important for being physically active across the lifespan (van Sluijs et al.,

2021). However, most evidence suggests that school-based promotion programs are unsuccessful at increasing short-term everyday PA levels, because the quality of PA programs is essential for its effectiveness, and previous programs are often not sufficiently engaging (Lubans et al., 2017). Thus, we should rethink *how* PA and physical education in schools can be designed to be enjoyable for youth and to increase everyday PA levels. Problems in the implementation and youth adherence to the programs represents another limitation in the school-based programs (van Sluijs et al., 2021). It is therefore important to *integrate children's and adolescents' perspectives and interests* when developing PA programs, and novel and creative alternatives need to be considered. This can be achieved by integrating (b) the social and digital environment of youth. Family and peers could be incorporated into PA promoting programs, because evidence suggests that parental modeling (Yao & Rhodes, 2015) and social support (Mendonça et al., 2014) are related to higher PA levels. Further, because of the globally increasing internet use in the last two decades, internet-based (eHealth) or mobile-based (mHealth) PA programs are a promising method to reach a large population of youth and to increase the perceived appeal for children and adolescents. Evidence suggests positive effects on short-term changes in adolescents' PA levels, with programs integrating new technology and more traditional intervention techniques yielding most promising results (van Sluijs et al., 2021). Lastly, it is important to consider (c) the living environment of children and adolescents. Their environment is of central importance for unstructured PA activities and active commuting, with the latter contributing a considerable amount to everyday PA (van Dijk et al., 2014). Thus, (political) attempts to promote PA in everyday life should specifically target traffic exposure, safety features as well as infrastructure for walking and cycling (Nordbø et al., 2020). Especially in urban environments, opportunities for active commuting as well as play including sport and fitness should be integrated. A survey among adolescents in 73 countries revealed that approximately 40 percent never actively commuted to school (van Sluijs et al., 2021). Thus, creating walking- or cycling-friendly environments (e.g., separate bike lanes) and specifically promoting active commuting could substantially increase everyday PA and accordingly improve related psychological correlates in childhood and youth.

Another important aspect when planning interventions or initiatives to promote PA in youth, is to adapt them to the individual. Previous evidence suggests that adolescents are more likely to meet the WHO guidelines when the performed PA is in accordance with their individual preferences (Fromel et al., 2017). Such individual preferences could possibly explain the between-person differences observed in the within-person associations between everyday PA and psychological correlates in this dissertation (*Study 2* of *Manuscript 2*, *Manuscript 3*).

Thus, potential between-person moderators should be incorporated in the planning, implementation and distribution of programs aimed at directly increasing PA levels to meet the WHO guidelines, or aimed at indirectly improving cognitive functioning or mental health through everyday PA. As previously highlighted, ambulatory assessment studies are specifically appropriate to examine such moderators, and they can help design and deliver goal-oriented and impactful interventions in individuals' natural contexts. Such interventions are often referred to as *ecological momentary interventions* and represent individually tailored interventions that can be automatically provided over mobile device at the time of interest and within the relevant context (Heron & Smyth, 2010). They can be operated in a timely manner, adapted to the underlying theory of change. For example, if administered at the right time, such interventions can be especially helpful at overcoming the intention-behavior gap between health behavior goals and exhibited health behavior like PA (Reichert et al., 2020). For this, it is important to investigate and understand antecedents of PA – or physical inactivity – as well as the time scales on which the relation occurs with ambulatory assessment studies. They can be used to send timely reminders and encouraging feedback to individuals (Reichert et al., 2020). First evidence supports the feasibility and effectiveness of ecological momentary interventions to promote everyday PA in different age groups, including children and adolescents (Fiedler et al., 2022; Guthrie et al., 2015; Schembre et al., 2018).

With increasing sensor monitoring like step counts through mobile phones or smart watches, new possibilities for ecological momentary interventions arise. In a simplified manner, individuals including children and adolescents already use similar features for example on smart watches, informing them about their daily step count and prompting them to take more steps. However, more research is still necessary to better understand antecedents and consequences of PA in everyday life. Only with a better understanding of why children and adolescents are (not) physically active at a specific time and within a particular context can we intervene and promote PA in real-time and real-life.

6. Conclusion

Living a physically active life is of central importance for cognitive and mental health aspects across the lifespan, and PA in developmentally sensitive phases of childhood and adolescence can be especially important for the individual development. Findings from this dissertation suggest that the association between everyday PA and psychological correlates – namely, EF and well-being – differs across age groups in childhood and youth. Further, the ambulatory assessment study designs presented in this dissertation allow to draw conclusions about the association on different time frames between as well as within individuals. The examination of short-term within-person associations is especially interesting and yields new insight into the role of everyday PA for cognitive and mental health outcomes in children and adolescents, showing for example that *every day of PA matters*. The examination within youth's realistic environment further facilitates the transfer of this dissertation's findings to practice. Nevertheless, more research is necessary to better understand everyday PA and its antecedents as well as consequences in children's and adolescents' daily lives to better promote everyday PA and ultimately foster (mental) health promotion and educational success. For this, ambulatory assessment examining *real-life* and *real-time* associations between and within individuals could be especially informative, granting promising new insights regarding individualized and tailored promotion and prevention approaches like ecological momentary interventions.

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Appendix

Appendix A: Manuscript 1

Executive Function and Physical Activity in Preschoolers: Does Hyperactive-Impulsive Behavior Moderate this Association?

Eppinger Ruiz de Zarate, A., Kerner auch Körner, J., Haas, P., Gunzenhauser, C., Rauch, W., & Gawrilow, C. (2024). Executive function and physical activity in preschoolers: Does hyperactive-impulsive behavior moderate this association? *Manuscript in Preparation*.

Executive Function and Physical Activity in Preschoolers: Does Hyperactive-Impulsive Behavior Moderate this Association?

Abstract

Previous experimental research suggests a positive association between executive function (EF) and physical activity (PA). Observational research specifically examining PA in everyday life does not consistently support this positive association, with findings often yielding negative or no associations. Hyperactive-impulsive behavior could act as a possible moderator, explaining inconsistent findings. In this observational study, we examined the relation between EF and everyday PA as well as hyperactive-impulsive behavior as a potential moderator in a sample of 68 German preschoolers (3-5 yrs). To objectively measure EF and PA, participants performed a computerized EF test battery (EF Touch) in two sessions and wore an accelerometer for seven days. Parental questionnaires were employed as subjective measures of EF, PA, and hyperactive-impulsive behavior. We only observed an association between objective and subjective measures of EF. Objectively measured moderate-to-vigorous PA was negatively related to EF performance, and hyperactive-impulsive behavior did not moderate this association. Neither time spent in any other PA intensity nor parental PA reports were related to EF performance. The findings yield new insight into the relation between PA in everyday life and preschoolers' EF, as the unexpected negative relation could not be explained through hyperactive-impulsive behavior. Our results are discussed considering methodological limitations, and possible directions in future research (e.g., combining objective and subjective measures of PA) are presented.

Keywords

Physical activity, accelerometry, executive function, hyperactive-impulsive behavior, preschoolers

Introduction

For a child to pursue any goal, being able to regulate their thoughts, emotions, and behavior is of central importance (Diamond, 2013). For such regulation, a child needs to acquire different cognitive abilities throughout their development: First, the child needs to be able to suppress predominant reactions in favor of alternative and less dominant reactions – also known as *inhibition*. For example, if a child wanted to join other children in their game, the child would need to inhibit the impulse to grab the toy before their turn. Second, a child needs to be able to keep information in mind and update it to align their reactions in a goal-directed manner – also known as *working memory*. In the presented example, the child would need to keep the rules of the game in mind and monitor when it was their turn to play. Third, the capacity to alternate between different mindsets as circumstances require it is necessary, referred to as *shifting*. In the given example, the child would need to adapt to the games' rules and could possibly profit from applying rules previously known from other games.

These higher-order cognitive functions are commonly referred to as *executive functions* (EF), and they have predictive value for educational achievement (Cortés Pascual et al., 2019), as well as living a healthy life (Gray-Burrows et al., 2019). In their integrative model, Miyake et al. (2000) described EF as one common underlying factor with inhibition, working memory, and shifting as three somewhat correlated but distinct components. This structure of EF has repeatedly been replicated in different samples, but a recent meta-analysis supports a greater unidimensionality of EF in childhood and adolescence compared to adulthood (Karr et al., 2018). This could be explained by differential developmental trajectories of the EF components in childhood (Diamond, 2013): while first forms of inhibition and working memory can already be observed in infants, shifting as the most complex EF component develops somewhat later (Garon et al., 2008). All components undergo a developmental shift during preschool age, but their development continues through adolescence into young adulthood (Huizinga et al., 2006). Thus, preschool age represents an important phase for the EF development. Because of the high relevance of EF throughout the lifespan, the investigation of potential ways to promote EF development have gained increased attention and popularity (Takacs & Kassai, 2019). A broad body of research has focused on means of promoting children's EF directly (e.g., computerized EF training), but programs aimed at improving EF might also be indirectly associated to EF through increased self-efficacy, or improved physical fitness (Diamond, 2012).

Executive Function and Physical Activity

An easily and widely applicable approach to indirectly promote EF is through physical activity (PA), referring to any bodily activity that increases an individual's energy expenditure

(Caspersen et al., 1985). Numerous previous findings consistently support a positive association of PA and EF in older adults (Chen et al., 2020; Colcombe & Kramer, 2003), whereas there are fewer as well as less consistent empirical results for children (Prakash et al., 2015) – especially in preschoolers. Because of the fast developmental changes in this age group, findings from older age groups may not be transferrable and preschoolers might be especially susceptible to beneficial PA-related effects on EF (Ludyga et al., 2016). Yet, investigating this association in preschoolers is a relatively new and growing area of research (Carson et al., 2016). In their meta-analysis of seven studies in early childhood, Carson et al. (2016) found a positive relation between PA and EF. Despite inconsistencies in findings, the authors highlighted that none of the reviewed studies reported detrimental effect of increased PA on EF. However, more recent studies in preschool samples also reported negative associations between PA and EF, and such inconsistencies might possibly be explained by the implemented study design.

The relation between PA and EF can be investigated with experimental or correlational (i.e., observational) study designs. Experimental studies allow conclusions about the effect of increased PA levels on EF and have often been implemented in previous research in youth (Carson et al., 2016; Wickel, 2017). A meta-analysis of ten experimental studies revealed small positive effects of chronic PA interventions (i.e., duration of > 4 weeks) on preschoolers' overall EF, inhibition, and working memory, and a moderate effect on preschoolers' shifting (Li et al., 2020). However, such findings are not necessarily transferrable to the effect of PA exhibited in everyday life. Observational studies can examine PA performed in individuals' everyday lives, which is especially interesting to understand how a physically active lifestyle influences EF performance and development, independent of specific PA interventions.

Studies examining PA in everyday life suggest a positive relation with EF, but only a limited number has employed accelerometers as a direct and valid measure of PA (Donnelly et al., 2016). Correlations between questionnaire- and accelerometer-assessed PA levels are low-to-moderate (Adamo et al., 2009), limiting the comparability between studies. Further, it is not yet fully understood how aspects of PA quantity (e.g., frequency, duration) are related to EF in preschoolers (Carson, Lee, et al., 2017), and accelerometers allow to objectively quantify PA. An often-examined measure of quantity is time spent in different PA intensities, ranging from light PA (e.g., walking below 4 km/h) to moderate PA (e.g., walking with 4-7 km/h) and vigorous PA (e.g., running with 7 km/h). In the literature, the most frequently examined intensity is moderate-to-vigorous PA (MVPA) which is positively associated with various health indicators (Carson, Lee, et al., 2017). Accordingly, the PA guidelines by the World Health Organization (WHO) recommend that averaged across one week children should

undertake 60 minutes of MVPA per day. In a network analysis, Bezerra et al. (2022) found that time spent in moderate PA was one of the most important variables for predicting better EF in preschoolers (e.g., compared to time spent in other PA intensities, fitness measures).

Positive associations between time spent in MVPA and EF have been reported in observational studies: seven-day MVPA but no time spent in any other PA intensity was positively related to inhibition (Luo et al., 2023), and in daily questionnaires, parents reported that their children (4-6 yrs) showed better attentional self-regulatory skills closely related to EF (i.e., concentrating, following through on a task) on days with more MVPA (Ludwig & Rauch, 2018). Reallocating as little as five minutes to MVPA (instead of sleep, light PA) was found to be related to better EF in preschoolers, but examining the direct association between MVPA and EF with a linear regression in the same sample revealed a negative association (Bezerra et al., 2020). This negative association was also supported in another study for all three EF components (Cook et al., 2019). However, samples from these studies reporting negative associations were preschoolers with low socioeconomic background from Brazil (Bezerra et al., 2020) or rural South Africa (Cook et al., 2019), with the latter sample exhibiting generally very high levels of MVPA but very low levels of structured PA. The authors argue that high levels of naturally occurring and unstructured PA (e.g., running around, playing with tires) and low levels of structured PA (e.g., teacher-arranged), often observed in lower-income settings, might not necessarily enhance EF development. The generalizability of these findings to samples from higher income countries (according to the world bank classification) or samples with a rather high socioeconomic background might therefore be restricted. In a large Australian cohort sample of preschoolers, MVPA was not related to any EF component, and time spent in light PA was negatively related to working memory (McNeill et al., 2018), while vigorous PA predicted better shifting one year later (McNeill et al., 2020).

Only one study employed the same highly differentiated and reliable test battery as in this study to measure EF in preschoolers and to investigate its association to PA: Willoughby et al. (2018) examined a sample of 85 US preschoolers that completed the test battery and wore accelerometers for five weekdays. Contradicting their expectations, MVPA was negatively related to overall EF and to inhibition when controlling for child gender, age, Body-Mass-Index (BMI), and parental level of education. A negative trend was also apparent for working memory but failed to achieve significance. The authors did not examine the relation with shifting and highlighted the lack of PA measurement on weekends as a limitation to their study. As a possible explanation for the unexpected negative results, Willoughby et al. emphasized the role of hyperactive-impulsive behavior, since children exhibiting higher hyperactive-impulsive

behavior might engage more time in higher intensity PA (Howie et al., 2013).

The Role of Hyperactive-Impulsive Behavior

In line with Willoughby et al.'s (2018) argument, MVPA was related to externalizing problems in a sample of preschoolers (McNeill et al., 2020). Attention deficit hyperactivity disorder (ADHD) represents one form of externalizing disorders closely linked to EF deficits (Barkley, 1997), with hyperactive-impulsive behavior as a main symptom (American Psychiatric Association, 2013). While symptoms of ADHD can already emerge in preschool age, ADHD is typically diagnosed later in childhood (Huss et al., 2008). Findings from older ADHD populations can yield important insights into the role of hyperactivity for the association between PA and EF also in preschool age. Previous research supports differences in PA levels between children with ADHD and the general population (Bundgaard et al., 2018; De Crescenzo et al., 2016), and parent-reported hyperactivity is related to higher objectively measured PA levels in clinical (Kofler et al., 2016) and non-clinical samples (e.g., Burley et al., 2022). Further, experimental studies in older children and adolescents with ADHD suggest that PA interventions are beneficial for EF (Montalva-Valenzuela et al., 2022). It has been reported that PA levels in childhood predict ADHD symptomatology in adolescence (Brandt et al., 2020), and a longitudinal nation-wide German survey for children and adolescents showed that MVPA in preschool age might be specifically beneficial for the EF development across childhood (Ganjeh et al., 2022). For instance, MVPA was associated with more favorable and adaptive changes in ADHD-symptomatology (i.e., hyperactivity/impulsivity and inattention) across one year in preschoolers with lower EF capacity and possibly at-risk for ADHD (Hoza et al., 2020).

The role of physical activity – a key component of hyperactivity – for ADHD is still discussed in the literature: Hyperactivity is a core symptom and thus a core diagnostic feature of ADHD, seen as ubiquitous and a reflection of a deficit to inhibit task-irrelevant behavior (Barkley, 1997). The functional working memory model argues that hyperactivity could be a compensatory mechanism facilitating cognitive functioning in ADHD populations (Rapport et al., 2009). Accordingly, during tasks with high EF demands, higher PA levels might compensate for lower EF capacities in children with ADHD. In line with this model, a meta-analysis of 63 studies suggests that PA levels in ADHD populations are specifically high during high EF demand settings (Kofler et al., 2016). Some evidence with older children suggests that PA during cognitive tasks is positively related to inhibition (Hartanto et al., 2016) and working memory (Sarver et al., 2015) in children with ADHD but not in typically developing peers.

However, first evidence suggests that performance in shifting tasks might not benefit from increased PA levels regardless of ADHD-symptomatology (Irwin et al., 2020).

Most research thus far has examined older children and clinical samples. First evidence from a sample of non-clinical but at-risk younger children (aged 5-7 yrs) with developmental difficulties – and specifically with early ADHD symptoms – showed that in this age group PA levels also increase during a task with high EF load (Burley et al., 2022): Elevated PA levels during the inhibition task were related to lower task performance but only in preschoolers with high hyperactivity symptoms, suggesting that hyperactive-impulsive behavior moderates the relation between PA and EF in young children. However, it is not clear whether and how these findings can be transferred to PA levels exhibited in everyday life rather than during challenging EF tasks. It is not yet definite whether MVPA in everyday life may be specifically positively related to EF in children with higher levels of hyperactive-impulsive behavior (Gapin & Etnier, 2010; Hoza et al., 2020) or in children with lower levels (Willoughby et al., 2018). Further research examining the potential moderating role of hyperactive-impulsive behavior on the association between everyday PA and EF in preschoolers is necessary.

Present Research

The central aim of our study was to examine the association between everyday PA and EF in preschool children. For this, we conducted a study with 68 preschoolers that completed the German version of the EF Touch (Ulitzka et al., 2023) and objectively measured their PA for seven consecutive days. Further, we presented parents with questionnaires to subjectively measure EF and PA.

We expected an association between objective and subjective measures for both PA (H1.1) and EF (H1.2). Since observational findings suggest a positive association between PA and EF in older samples and some also support this in younger children, Hypothesis 2 expected that the relation between objectively measured MVPA and EF would be positive (H2.1). Additionally, we hypothesized that controlling for hyperactive-impulsive behavior would improve the prediction of total EF (H2.2). Another aim of our study was to investigate Willoughby et al.'s assumption that hyperactive-impulsive behavior could explain the negative association between MVPA and EF. Thus, we hypothesized that hyperactive-impulsive behavior would moderate the relation between MVPA and EF (H3).

In explorative analyses, we further wanted to examine (1) if MVPA would be differently related to the specific EF components (i.e., inhibition, working memory, shifting), and (2) if time spent in distinct PA intensities (i.e., light, moderate, vigorous) would be differently related to overall EF. Additionally, if subjective and objective measures of PA were not at least

moderately positively related in our study, we wanted to examine (3) if parent-reported PA levels would be positively related to total EF.

Methods

Procedure and Participants

This study was part of a wider project aiming to standardize and validate the German version of the EF Touch test battery (*ExFunKi – Exekutive Funktionen im Kindergarten*). It was approved by the ethic committee of the German Psychological Society (KörnerJulia2020-01-28WV). In total, data was collected from 442 German preschoolers (aged 3-5 yrs), with procedures and implemented measures varying between sub-samples depending on the validation condition. An extensive description of the project can be found in the study protocol (in prep.). For our analyses, we only used data of a specific sub-sample from the project wearing an accelerometer and we will therefore only describe the procedure and measures relevant for this sub-sample.

For the sub-sample used in this study, caregivers were instructed to let their children wear an accelerometer for seven consecutive days, measuring their child's PA. We received written consent for 80 children for this sub-sample. In total, 12 children had to be excluded from analyses due either to insufficient PA data recording with the accelerometer (n = 5), missing data in the EF tasks (n = 1), insufficient understanding of the EF tasks (n = 1), or missing data on hyperactive-impulsive behavior (n = 5).

Thus, the final sample size consisted of 68 preschoolers, with an equal number of female (n = 34) and male (n = 34) participants. On average, participants were aged 56.41 months (SD = 8.91 mths; range 36.26-71.81 mths) and had an average BMI of 15.39 (SD = 1.68; missing n = 13). Regarding the parental level of education, 72.06% of families showed high, 16.18% average, and 10.29% low levels (for classification see Ulitzka et al., 2023).This sub-sample was recruited in regional kindergartens and through university-wide e-mails at the University of Tübingen (Southwestern Germany; n = 55) and the University of the Federal Armed Forces Hamburg (Northern Germany; n = 13). After receiving parental written consent, preschoolers were individually tested by one instructor either in their kindergarten (n = 42) or in the laboratory at the university (n = 22) at two separate appointments; these could either be scheduled on the same day with a break or on two different days.

At the start of the first appointment, preschoolers were informed in an age-appropriate way about the experiment and the accelerometer measurement, they were asked for their verbal consent, and were shown how to wear the accelerometer. Afterwards, they completed the first

part of the computerized EF tasks (i.e., EF Touch), consisting of a short training task and the first five EF Touch subtests. In the second appointment, preschoolers completed the remaining two EF Touch subtests (see *Table 1*). After completing the EF Touch test battery, the investigator measured children's height and weight.

Accelerometers were either collected at the participating kindergartens or participants' parents brought them back to the university after completion of the data collection. Participation was voluntary, and preschoolers received a small present as well as a certificate after each appointment. Parents received information about their child's PA, and kindergartens were rewarded with a book about EF as well as an optional workshop.

Material

Executive Function

EF Touch. To objectively measure preschoolers' EF, we implemented the German version of the EF Touch (Ulitzka et al., 2023), originally developed by Willoughby and Blair (2011). The EF Touch is a computerized test battery conducted on a 15-inch touch screen, consisting of one training task measuring reaction time (RT) and seven age-specific tasks measuring EF. Regarding the separate EF components, three tasks measured inhibition, three working memory, and one task measured shifting. **S**hort descriptions of each task can be found in *Table 1*. After each task, instructors indicated the child's comprehension on a 10-point Likert-scale (*How well did the child understand the task?* from *1 – not at all* to *10 – very well understood*) and noted any further comments in an open format.

In line with previous analyses of the German EF Touch (Ulitzka et al., 2023), we excluded trials with RT of less than 200 ms in tasks with RT measurement. For trials with RT deviating more than 1.5 of the interquartile range from the individual mean RT, we inspected investigators' answers to the protocol question about the child's understanding as well as further comments. If investigators indicated problems with a child's comprehension in the protocol question (scores 1-3) or problems in test application (e.g., external disturbance), data from the respective tasks was excluded from the analysis (see *Table 1*). For tasks without RT measurement, we also inspected investigators' comments and excluded data equivalently as depicted in *Table 1*.

Table 1

Description of the EF Touch Tasks, Including the Correspondent Executive Function Component Measured

Task	Executive Function Component	Task Description	Items	Items for 3-Year-Olds	RT Measurement	Data Exclusion
		First Appointment				
Something's the Same	Shifting	Recognize similarities between pictures on three dimensions (color, size, shape)	30	20	No	4[a]
Arrows	Inhibition	Press button in direction that arrow points at (congruent, incongruent trials)	36	All	Yes	3
Houses	Working Memory	Remember animal(s) and color(s) of house(s)	18	0	No	4
Pig (Go/NoG)	Inhibition	Press button when animals are presented; except for pig	40	All	Yes	4
Farmer	Working Memory	Remember movements of animals across a 4X4 matrix	36	8	Yes	3
		Second Appointment				
Pick the Picture	Working Memory	Select each picture once; position of pictures rotates	32	All	No	4
Silly Sounds Game (Stroop)	Inhibition	Press cat when hearing bark, press dog when hearing meow	17	All	Yes	2

Note. Items for 3-year-olds describe the number of items presented in this age group; some items were omitted because of increased task difficulty. Data exclusion specifies the number of children for which data from the task was excluded because of problems in the task administration (e.g., external disturbance) or limited understanding of the task/instruction. [a] For two additional children, data was excluded for the second part of the task because of limited understanding.

After data exclusion, we calculated accuracy scores (in percent: 1-100) for each EF Touch task, considering the number of presented items (age-specific). Ulitzka et al. (2023) found that the tasks sufficiently differentiate between the three EF components, but because of high interrelations between the components the one-factor EF model represented the data better. Thus, we computed a total EF score averaging the accuracy scores of all EF Touch tasks to capture children's EF competence, but we also conducted exploratory analyses with the single EF component measures (i.e., inhibition, working memory, shifting) by calculating the average accuracy across the respective EF Touch tasks.

BRIEF-P. As a subjective measure of EF, we employed the German version of the *Behavior Rating Inventory of Executive Function – Preschool Version* (BRIEF-P; Daseking & Petermann, 2013), consisting of 63 items. Parents rated how often their child's exhibited behaviors presented a problem during the last six months (e.g., *Was impulsive* or *Needs support from adults to stay focused on one task*) on a 3-point scale (*'never'*, *'sometimes'*, or *'often'*). We calculated the mean score for all answers (range 1-3), with higher values implying lower executive function. The scale showed a very high reliability $\alpha = .96$.

Physical Activity

Accelerometer. To objectively measure PA, participants wore an Actigraph GT3X+ (Actigraph, LLC, Fort Walton Beach, Florida). During the first appointment, the investigator showed the children the accelerometer and explained in an age-appropriate way what it measured and how to wear it on their hip on the non-dominant side. Participants wore the accelerometer for seven consecutive days, measuring PA in 15 second epochs.

The analysis of accelerometer data followed established guidelines regarding data exclusion, valid wear time, and cut-points: To categorize different PA intensities, we applied the age-specific cut-points defined by Pate et al. (2006) for the vertical axis 1, shown to most accurately classify MVPA (Janssen et al., 2013) and previously employed in similar work (Willoughby et al., 2018). We classified 20 minutes of consecutive zeros as non-wear time. Days with at least six hours of wear-time were defined as valid days, and children with at least three valid days were included in the analysis (Bingham et al., 2016). We calculated the proportional time spent in each PA intensity (MVPA, light, moderate, vigorous, sedentary) by dividing the minutes spent in the correspondent intensity across the seven days through the total minutes of collected PA data.

PA questionnaire. As a subjective measure of PA, we implemented a short parental questionnaire (Bayer et al., 2012). Parents described their child's regular PA by answering seven items (e.g., *How often does your child play with a ball?* or *Does your child attend a sports*

club or sports group?) on 5- to 6-point scales, and answers were defined as high (+1) or low (-1) levels of PA. As suggested in previous work with this questionnaire (Haas et al., 2022), we calculated the sum score of all answers (-7 to 7) as a continuous measure of PA. In our sample, the scale showed a very poor reliability $\alpha = .36$. We would argue that the questionnaire is still interpretable regards content and theoretical background despite the low numerical alpha value (Cronbach, 1951). The PA questionnaire assesses the frequency of different types of PA (e.g., playing with a ball, attending a sports club), which can occur independent of each another. Thus, to discriminate and assess these distinct types of PA, high alpha values are not necessarily desirable (Taber, 2018).

Hyperactive-Impulsive behavior

Hyperactive-impulsive behavior was measured using the parent-report version of the German translation of the *Strengths and Difficulties Questionnaire for Preschoolers* (SDQ 2-4; Klein et al., 2013). We calculated the mean score of the respective scale *Hyperactivity*, including 5 items (i.e., restless, overactive, cannot stay still for long; constantly fidgeting or squirming; easily distracted, concentration wanders; thinks things out before acting; sees tasks through to the end, good attention span). The hyperactivity scale thus comprises all three symptom categories of ADHD (i.e., hyperactivity, impulsivity, inattention). The items for the hyperactivity scale are the same as in the version SDQ 4-17. Parents rated their child on a 3-point Likert-scale (*1 – not applicable* to *3 – clearly applicable*), with higher values implying more hyperactive-impulsive behavior. The scale showed a very good reliability $\alpha = .83$.

Background Measures

Parents answered questions about their children's age and gender, as well as level of education for both parents on a five-point scale ranging from *1 – No high school graduation* to *5 – University-entrance diploma ["Abitur"]*. In line with previous analyses (Ulitzka et al., 2023), the level of education of both parents was averaged and then rounded down. If level of education was just indicated for one parent, this value was used as a proxy. Further, to calculate children's Body-Mass-Index (BMI), investigators measured children's height and weight.

Data Analysis

Analyses were pre-registered (see: https://osf.io/v9fc4/?view_only=bfab58215c314f97a7271abe1bcbc774) and conducted with R version 4.3.2 (R Core Team, 2023), using $\alpha = .05$ to denote statistical significance. Regarding data preparation of the EF Touch, we had only pre-registered data exclusion based on investigator's comments for the tasks with RT measurement. However, in addition to the pre-registration, we conducted a parallel data exclusion for tasks without RT measurement.

We tested the association between objective and subjective measures of PA (H1.1) as well as EF (H1.2) with two separate correlation tests. To test the Hypotheses H2.1 and H2.2 regarding the association between PA and EF, we used linear regression models with total EF as outcome and MVPA as predictor. In Model 1 (H2.1), we controlled for age, child gender, BMI, and parental level of education, and in Model 2 (H2.2), we additionally controlled for hyperactive-impulsive behavior. All control variables and the predictor were centered on the grand mean. To test if hyperactive-behavior moderated the relation between MVPA and total EF (H3), we included an interaction term between MVPA and hyperactive-impulsive behavior in Model 3, multiplying the respective variables. For all linear regression models, we checked for linearity, normality, homoscedasticity, and outliers to ensure model assumptions were not violated. Outliers were excluded, and in cases of heteroscedasticity we calculated Weighted Least Squares to account for unequal variance of observations.

In the exploratory analyses, we again conducted linear regression models, controlling for age, child gender, BMI, parental level of education, and hyperactive-impulsive behavior: For Explorative Analysis 1, we used MVPA as predictor and conducted three separate models with (a) inhibition, (b) working memory, and (c) shifting as outcomes. For Explorative Analysis 2, we included proportional time spent in different PA intensities (light, moderate, vigorous) as predictors, and total EF Touch score as outcome. For Explorative Analysis 3, we used the parent-reported PA level as predictor and total EF Touch score as outcome.

Results

Descriptive Results

Data availability as well as descriptive results of accelerometer and EF Touch data are summarized in *Table 2*. For more than half of the sample (63.24%), accelerometer data was available for the full seven days with an average of 10 hours of data collection per day (M = 10.04, SD = 2.50). During the data collection period, children spent approximately 51% of the time in sedentary behavior, 36% in light PA, and 13% in MVPA. On average, participants spent approximately 80 minutes per day in MVPA, fulfilling the WHO guideline of a weekly average of 60 minutes of MVPA per day. In the EF Touch, children on average showed a total EF Touch score of 72.02% (range 23.20-90.01). Correct responses were highest for inhibition (82.34% correct; range 23.20-100.00), followed by shifting (M = 77.90% correct; range 43.33-100.00) and working memory (M = 60.17% correct; range 28.47-90.62).

Table 2

Description of Objective Data for PA (Accelerometer) and Executive Function (EF Touch)

Variable	Metric	*N*	*M (SD)*
Accelerometer	Number of valid days (max. 7)	68	6.69 (1.33)
	Total wear-time (hrs/day)	68	10.04 (2.50)
Daily Physical Activity Level	Sedentary (mins/day)	68	307.8 (97.46)
	Light (mins/day)	68	214.76 (59.24)
	Moderate-to-vigorous (mins/day)	68	79.86 (30.43)
Executive Function	Total (% correct)	68	72.02 (11.95)
	Inhibition (% correct)	67	82.34 (16.10)
	Working Memory (% correct)	66	60.17 (13.13)
	Shifting (% correct)	65	77.90 (14.91)

In the parental questionnaire, overall parents described their children's PA level as intermediate ($M = 0.45$, $SD = 2.91$) and EF capacity as medium ($M = 1.57$, $SD = 0.33$). They described children's hyperactive-impulsive behavior as relatively low ($M = 0.65$) and the variability in the sample was also low ($SD = 0.50$).

Bivariate Associations between Assessed Variables

Unsurprisingly and as indicated in the correlation matrix (see *Table 3*), we observed significant correlations between total EF Touch score and all EF components assessed with the EF Touch as well as between the single EF components. Time spent in MVPA was related to more time spent in light PA and less time in sedentary behavior. Further, children's age correlated significantly positively with total EF Touch score, inhibition, and shifting as well as sedentary behavior, but negatively with time spent in MVPA. Thus, MVPA levels decreased with age, while time spent sedentary increased. Parents' answers in the BRIEF-P were positively correlated with hyperactive-impulsive behavior, implying that if parents reported lower EF for their child, they reported more hyperactive-impulsive behavior.

Hypothesis Testing

To examine the association between objective and subjective measures, we conducted two separate correlation tests for PA (H1.1) and EF measures (H1.2). Results revealed no significant correlation between objectively measured MVPA and parental reports in the PA questionnaire ($r = 0.005$, $t(65) = 0.040$, $p = .968$), while total EF Touch score and parental reports in the BRIEF-P were significantly correlated ($r = -.253$, $t(66) = -2.123$, $p = .036$).

To test H2 concerning the association between MVPA and total EF Touch score, we ran two multiple linear regression models, displayed in *Table 4*. In Model 1 testing H2.1, we

controlled for possible confounders (i.e., age, child gender, BMI, parental level of education), and in Model 2 testing H2.2, we additionally controlled for hyperactive-impulsive behavior. Since Model 2 did not predict the data significantly better than Model 1 ($F(1, 58) = 1.003$, $p = .321$, $f^2 = .686$), controlling for hyperactive-impulsive behavior did not significantly improve the prediction of total EF Touch score. Accordingly, we used Model 1 to investigate the relation between MVPA and EF: more time spent in MVPA was related to significantly lower total EF Touch score ($\beta = -0.69$, $p = .017$). Further, age was related to better EF ($\beta = 0.41$, $p = .001$) as was parental level of education ($\beta = 2.28$, $p = .021$).

To examine whether hyperactive-impulsive behavior possibly moderated the relation between MVPA and EF (H3), we added the interaction term between MVPA and hyperactive-impulsive behavior to the multiple linear regression in Model 3. Results can be inspected in *Table 4*. Again, time spent in MVPA was significantly and negatively related to total EF Touch score ($\beta = -0.75$, $p = .010$). The interaction between MVPA and hyperactive-impulsive behavior was not significant ($\beta = 0.80$, $p = .137$); thus, hyperactive-impulsive behavior did not moderate the association between MVPA and total EF Touch score. Concerning the confounding variables, age ($\beta = 0.43$, $p = .001$) and parental level of education ($\beta = 2.20$, $p = .024$) were again related to better EF.

Table 3

Bivariate Correlations between Objective and Subjective Measures of Physical Activity and Executive Function

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Sedentary Behavior	-									
2. Light Physical Activity	**-.91** ***	-								
3. MVPA	**-.81** ***	**.48** ***	-							
4. EF Touch – Total Score	**.31** **	-.19	**-.39** **	-						
5. EF Touch – Inhibition	**.27** *	-.18	**-.31** *	**.87** ***	-					
6. EF Touch – Working Memory	.21	-.12	**-.27** *	**.73** ***	**.32** **	-				
7. EF Touch – Shifting	.05	.00	-.12	**.59** ***	**.38** **	**.33** **	-			
8. Hyperactivity/Impulsivity	.03	-.01	-.05	-.23	-.17	-.09	-.21	-		
9. BRIEF-P	-.01	.03	-.03	**-.25** *	-.16	**-.25** *	-.22	**.73** ***	-	
10. Physical Activity Questionnaire	.10	-.15	.01	-.02	.03	.02	-.07	-.02	-.18	-
11. Age	**.25** *	-.20	**-.25** *	**.54** ***	**.64** ***	.20	**.36** **	-.16	-.13	.15

Note. * $p < .05$, ** $p < .01$, *** $p < .001$; Objective measures of physical activity refer to proportional time spent in specific physical activity intensity: MVPA – moderate-to-vigorous physical activity; BRIEF-P – parental questionnaire of executive function; age was calculated in months.

Table 4

Relation between MVPA and EF Total Score (Hypothesis 2) With Possible Moderating Effect of Hyperactive-Impulsive Behavior (Hypothesis 3)

	Model 1			Model 2			Model 3		
	Est.	CI	*p*	Est.	CI	*p*	Est.	CI	*p*
Intercept	**62.53**	**54.00 – 71.06**	**<0.001**	**62.98**	**54.40 – 71.55**	**<0.001**	**63.01**	**54.52 – 71.49**	**<0.001**
MVPA [in %]	**-0.69**	**-1.26 – -0.13**	**0.017**	**-0.74**	**-1.31 – -0.17**	**0.012**	**-0.75**	**-1.32 – -0.19**	**0.010**
Age	**0.41**	**0.17 – 0.65**	**0.001**	**0.39**	**0.15 – 0.64**	**0.002**	**0.43**	**0.18 – 0.68**	**0.001**
Gender (female)	1.46	-2.51 – 5.43	0.465	1.02	-3.05 – 5.09	0.619	1.29	-2.76 – 5.33	0.526
BMI	-0.58	-1.87 – 0.72	0.375	-0.45	-1.77 – 0.87	0.497	-0.36	-1.67 – 0.94	0.579
Parental education	**2.28**	**0.36 – 4.20**	**0.021**	**2.22**	**0.29 – 4.14**	**0.025**	**2.20**	**0.30 – 4.11**	**0.024**
Hyperactivity/Impulsivity				-2.08	-6.23 – 2.08	0.321	-1.92	-6.04 – 2.20	0.355
MVPA X Hyperactivity/Impulsivity							0.80	-0.26 – 1.87	0.137
N	65			65			65		
R^2	0.397			0.407			0.430		

Table 5

Relation between MVPA and Executive Function Components (Explorative Analysis 1)

	Inhibition			Working Memory			Shifting		
	Est.	CI	*p*	Est.	CI	*p*	Est.	CI	*p*
Intercept	**79.25**	**67.25 – 91.25**	**<0.001**	**43.60**	**30.37 – 56.82**	**<0.001**	**58.02**	**44.38 – 71.65**	**<0.001**
MVPA [in %]	-0.31	-0.92 – 0.30	0.320	**-0.98**	**-1.85 – -0.10**	**0.029**	-0.06	-0.97 – 0.85	0.894
Age	**0.72**	**0.42 – 1.03**	**<0.001**	0.25	-0.14 – 0.65	0.207	**0.69**	**0.30 – 1.09**	**0.001**
Gender (female)	1.47	-3.38 – 6.33	0.546	1.25	-4.96 – 7.47	0.688	**9.11**	**2.37 – 15.86**	**0.009**
BMI	-1.13	-2.81 – 0.56	0.185	1.72	-0.61 – 4.05	0.144	-0.41	-2.57 – 1.74	0.701
Parental education	0.82	-1.83 – 3.46	0.540	**3.59**	**0.66 – 6.52**	**0.017**	**3.69**	**0.66 – 6.73**	**0.018**
Hyperactivity/Impulsivity	-0.87	-6.24 – 4.49	0.746	-1.34	-7.70 – 5.02	0.675	1.64	-5.64 – 8.91	0.654
N	65			63			31		
R^2	0.385			0.259			0.362		

Note. Multiple regression for Inhibition was calculated with Weighted Least Squares because of heteroscedasticity.

Table 6

Association between Time Spent in Different Physical Activity Intensities and Total Executive Function Touch Score (Explorative Analysis 2)

	Est.	CI	*p*
Intercept	**62.99**	**54.32 – 71.65**	**<0.001**
Light PA [in %]	-0.22	-0.69 – 0.24	0.339
Moderate PA [in %]	-0.40	-1.97 – 1.17	0.613
Vigorous PA [in %]	-0.91	-3.01 – 1.18	0.385
Age	**0.37**	**0.12 – 0.63**	**0.004**
Gender (female)	1.02	-3.25 – 5.29	0.633
BMI	-0.45	-1.80 – 0.90	0.504
Parental education	**2.22**	**0.27 – 4.17**	**0.027**
Hyperactivity/Impulsivity	-1.99	-6.20 – 2.21	0.346

Note. $N = 65$, $R^2 = 0.417$.

Exploratory Analyses

We also examined the association between objectively measured MVPA and EF components in separate multiple regression models (Explorative Analysis 1), controlling for age, gender, BMI, parental educational level, and hyperactive-impulsive behavior (see *Table 5*). Contradicting Willoughby et al.'s (2018) results, we found that MVPA was significantly related to lower working memory (β = -0.98, p = .029), while there was no significant association with inhibition (β = -0.31, p = .320) or shifting (β = -0.06, p = .894).

Further, in Explorative Analysis 2, we inspected how time spent in different PA intensities (light, moderate, vigorous) was related to total EF Touch score in one multiple regression model, controlling for the same confounding variables as in the previous explorative analysis (see *Table 6*). We found that no time spent in any PA intensity was significantly related to total EF Touch score (light PA: β = -0.22, p = .339; moderate PA: β = -0.40, p = .316; vigorous PA: β = -0.91, p = .385). To investigate the association between parent-reported PA and EF, we ran a separate multiple regression model with the same confounding variables (see *Table 7*). No association between parent-reported PA and children's total EF Touch score was evident (β = -0.36, p = .329). Only age was significantly related to higher EF (β = 0.64, p < .001).

Table 7

Association between Parent-Reported Physical Activity and Total EF Touch Score (Explorative Analysis 3)

	Est.	CI	*p*
Intercept	**62.19**	**53.06 – 71.33**	**<0.001**
Parent-reported PA	-0.36	-1.10 – 0.37	0.329
Age	**0.64**	**0.38 – 0.90**	**<0.001**
Gender (female)	4.30	-0.09 – 8.70	0.055
BMI	-0.28	-1.72 – 1.16	0.701
Parental education	1.92	-0.10 – 3.95	0.063
Hyperactivity/Impulsivity	-0.34	-4.89 – 4.20	0.880

Note. N = 65, R^2 = 0.400.

Given the positive correlation between sedentary behavior and total EF (see *Table 3*), we decided to examine this association – additionally to the pre-registered analyses – in a multiple regression model, controlling for the same confounding variables as in the previous exploratory analyses. Here, we found that sedentary behavior was significantly related to total EF Touch score, and again age and parental level of education were related to better total EF. The results can be found in the Appendix.

Discussion

In our observational study with 68 German preschoolers, we examined how PA in everyday life is related to EF and whether hyperactive-impulsive behavior influences this relation. For this, we implemented subjective and objective measures for both constructs: Parental questionnaires were employed to subjectively measure PA and EF. To objectively measure time spent in PA, participants wore an accelerometer for seven days. As an objective measure of EF, participants completed the German version of the EF Touch test battery. The first aim of our study was to examine how subjective and objective measures of the constructs were related. Second, we hypothesized that objectively measured MVPA would be positively related to EF measured with the EF Touch. Third, we expected that hyperactive-impulsive behavior would moderate this association between PA and EF.

Regarding PA, we did not find a significant relation between parent-reported PA and time spent in any PA intensity measured with the accelerometer. This aligns with previous research that showed differences in questionnaire- and accelerometer-derived PA levels in children (Adamo et al., 2009), although the original study validating the questionnaire used in our study reported positive correlations (Bayer et al., 2012). The parental PA questionnaire and the accelerometer might measure different aspects of PA: Whereas subjective measures can provide information about the specific type of PA, objective measures are believed to be more robust (Adamo et al., 2009), as they more reliably capture for example the irregular nature of children's PA in everyday life. Regarding EF, we found that parent-reported EF were related to objectively measured EF, in line with previous analyses using the German version of the EF Touch (Ulitzka et al., 2023). As hypothesized, if parents reported that their children showed more EF-related problems, the children performed worse in the EF Touch.

Contrary to previous findings supporting a positive association between PA and EF in older age groups (Chen et al., 2020; Colcombe & Kramer, 2003; Prakash et al., 2015) and some also in preschoolers (Carson et al., 2016; Tanaka et al., 2020), we observed a negative relation: In our study, we found that objectively measured MVPA was negatively related to EF – even when controlling for sociodemographic variables. This was in line with findings from Willoughby et al. (2018) who also implemented the EF Touch to measure preschoolers' EF performance and measured PA with accelerometers for five days. They likewise observed a negative association between MVPA and total EF Touch score. However, this result pattern contradicted both Willoughby et al.'s as well as our hypotheses.

A meta-analysis of seven studies in early childhood (Carson et al., 2016) suggested not only that PA was positively related to preschoolers' EF, but they emphasized that none of the

studies reported negative associations. Since most of those studies implemented experimental study designs, they examined PA as induced or enhanced through a specific intervention. In contrast, our study as well as Willoughby et al.'s study (2018) specifically investigated PA exhibited in preschoolers' everyday life within their natural environment. Interventions often include more structured PA types that might be specifically beneficial for EF (e.g., with high cognitive demands; Best, 2010). In contrast, an overall more physically active lifestyle may be related to less structured types of PA that might be less favorable for EF development (Cook et al., 2019) and, therefore, not necessarily be positively associated with EF. Accordingly, previous work examining objectively measured PA in everyday life mainly reported no associations between MVPA and total EF (Carson, Rahman, et al., 2017; Cook et al., 2019; McNeill et al., 2018), with only one study reporting a positive association (Luo et al., 2023). Besides Willoughby et al. (2018), two other studies also reported negative associations between everyday MVPA and EF in preschoolers in samples very different to our Western and highly educated samples (low-income Brazil: Bezerra et al., 2020; low-income, rural South Africa: Cook et al., 2019), suggesting that the negative association observed in our study might be generalizable to a variety of different populations. Yet, possible moderators should be further examined to better understand this unexpected result pattern in preschoolers compared to older samples.

Hyperactive-Impulsive Behavior as a Possible Moderator

Willoughby et al. (2018) argued that preschoolers' hyperactive-impulsive behavior might explain the unexpected negative relation between MVPA and EF: Preschoolers exhibiting higher hyperactive-impulsive behavior might engage in more PA (Howie et al., 2013) and possibly in types of PA that are less favorable for EF development (Cook et al., 2019). Previous research supports that children from clinical (Kofler et al., 2016) and non-clinical samples exhibiting more hyperactive-impulsive behavior (Burley et al., 2022) also showed higher objectively measured PA levels. This was not the case in our sample as parent-reported hyperactive-impulsive behavior was not related to time spent in any objectively measured PA intensity. Other lines of research have argued that PA might be especially positively related to EF in children with high levels of hyperactive-impulsive behavior (Gapin & Etnier, 2010). The functional working memory model (Rapport et al., 2009) proposes a possible explanation for this, as it views hyperactivity as a compensatory mechanism in children with ADHD. Children with high levels of hyperactive-impulsive behavior might compensate for lower EF capacities through higher PA levels.

Considering these contradicting arguments, one aim of our study was to examine

whether hyperactive-impulsive behavior moderates the relation between PA and EF. Our findings revealed that there was no moderation by hyperactive-impulsive behavior, as the interaction with MVPA was not significantly related to total EF Touch score. Further and contradicting our hypothesis, controlling for hyperactive-impulsive behavior did not significantly improve the prediction of preschoolers' EF. Thus, our findings do not support Willoughby et al.'s (2018) argument that the negative association between MVPA and EF could be explained through hyperactive-impulsive behavior. According to our findings, the relation between everyday PA and EF is neither stronger in children with high levels of hyperactive-impulsive behavior (Gapin & Etnier, 2010; Rapport et al., 2009) nor in those with low levels (Willoughby et al., 2018).

Investigation of Separate EF Components and PA Intensities

Since previous research findings have shown differential associations of EF components with PA as well as time spent in different PA intensities, we explored these separately. First, we examined how objectively measured MVPA was related to the three EF components: We observed a significant negative association between MVPA and working memory, whereas the associations with inhibition and shifting failed to reach significance. This was in line with findings from a meta-analysis suggesting that working memory might be specifically sensitive to beneficial effects of PA in youth (Alvarez-Bueno et al., 2017). Because of the distinct developmental trajectories of the different EF components (Diamond, 2013; Garon et al., 2008), working memory might be specifically susceptible to PA-related effects during preschool age. Still, this result pattern was unexpected since Willoughby et al. (2018) only found a significant negative relation with inhibition and a negative trend for working memory, supported by similar findings from Luo et al. (2023). In contrast to previous research findings reporting no association between objectively measured PA and any EF component (Carson, Rahman, et al., 2017; Mcneill et al., 2018), our results suggest that the association might indeed differ between EF components, but more research is necessary to better understand these distinct associations.

Second, we investigated the association between time spent in different PA intensities and EF, as previous research revealed inconsistent findings depending on the examined PA intensity (Bezerra et al., 2022; McNeill et al., 2018; Vabø et al., 2022). Here, we found that besides MVPA no time spent in any other PA intensity (light, moderate, vigorous) was significantly related to EF, even though negative trends were observable for all intensities. Third, since parent-reported and objectively measured PA were not related, we also examined the association between parent-reported PA and total EF Touch score. This analysis revealed no significant association. However, the PA questionnaire showed an extremely low reliability

in our sample, limiting the interpretability of this analysis. Our study supports the well-established finding that the comparability between different PA operationalizations (e.g. subjective vs. objective measurement) is restricted (Adamo et al., 2009). Given the limited number of previous studies targeting preschoolers and the differences in implemented measurement methods, more research is necessary to obtain an overarching understanding of the relation between PA and EF in the developmentally sensitive period of preschool age.

Lastly, because of the significant positive correlation between sedentary behavior and EF in our sample, we examined this association in addition to the pre-registered analyses. Even when controlling for sociodemographic confounders and hyperactive-impulsive behavior, more time spent sedentary was related to higher total EF Touch score. This was unexpected, as a review of 37 studies reported negative associations between sedentary behavior and cognitive development in early childhood (Carson et al., 2015). However, the authors pointed out that different types of sedentary behavior (e.g., watching TV vs. reading) might have different effects. A recent review of 16 studies examining the association between sedentary behavior and EF in youth (Li et al., 2022) reported that findings were mixed when sedentary behavior was measured with accelerometers, but most studies reported negative or no associations. However, none of the studies objectively measuring sedentary behavior included preschool samples, limiting the applicability of the results for our sample. More research is necessary to understand the association between sedentary behavior and EF in preschoolers, and investigating children's activities during sedentary time might be especially informative. In our study, parents had rather high educational levels, and might have structured their children's environment (Sarsour et al., 2011) and sedentary activities in a more favorable way for EF development (e.g., less screen time; Määttä et al., 2017), potentially explaining the positive association.

Limitations and Suggestions for Future Research

Despite the numerous advantages of observational study designs for the investigation of everyday PA, such designs do not allow any causal conclusions. This needs to be considered when interpreting our findings. The observed negative association between MVPA in everyday life and EF should not be interpreted as PA having a detrimental effect on EF. Rather, we think that it is important to carefully examine how different types of PA (apart from PA quantity) are distinctly and possibly positively related to EF. For example, PA incorporating mindfulness aspects (e.g., yoga; Diamond, 2012) or high cognitive load (e.g., team sports; Best, 2010) could be specifically beneficial for EF development. However, we measured time spent in PA with the accelerometer and the employed questionnaire only contained limited information regarding

the type of PA. Future research could aim at combining quantitative and qualitative aspects of everyday PA to better understand the role they play for EF in preschool age. This could explain inconsistent findings or null findings in previous research only examining quantitative aspects of everyday PA.

Previously, observational studies examining everyday PA and its relation to EF have often only measured EF performance once. The question arises to what extent different activity patterns are comparable regarding their relation to children's EF (Migueles et al., 2021) and whether these associations might differ over time. Repeatedly measuring children's EF performance while monitoring their PA yields insights into the association on smaller time frames and allows us to draw conclusions on the immediate effect of PA as well as over longer periods of time. Studies with such ambulatory assessment designs revealed that PA might be related to EF within the same day (Ludwig & Rauch, 2018) but that this association might also vary within the day (Eppinger-Ruiz de Zarate et al., 2024). Thus, future studies could focus on examining these smaller time frames to better understand the association between PA and EF in everyday life and within children's natural environment.

Our observational study design further restricts the interpretation of the observed positive association between sedentary behavior and EF, which might be reversed: children with higher EF might be more interested in EF-promoting activities performed sedentarily, such as reading. Thus, higher EF might account for children spending more time sedentary. These interests could be further promoted by parents or in preschools. Future studies could focus on examining the directionality of this association and further investigate the specific sedentary activities that might be beneficial for EF development (Carson et al., 2015).

In our sample, parent-reported hyperactive-impulsive behavior was not related to PA levels, contradicting previous findings (Burley et al., 2022; Kofler et al., 2016). Also, we observed no moderating effect of hyperactive-impulsive behavior on the relation between PA and EF, contradicting Burley et al.'s (2022) results: in their sample of five- to seven-year-olds with developmental difficulties and especially early ADHD symptomatology, hyperactive-impulsive behavior moderated the association between PA levels and EF performance, as the association increased with higher levels of hyperactivity. Burley et al. focused on PA during EF tasks, while we measured PA in preschoolers' everyday life, which might explain the different result pattern. They measured hyperactive-impulsive behavior with the same questionnaire as us (SDQ), but Burley et al. specifically examined a sample of children with developmental difficulties, while in our sample hyperactive-impulsive behavior was overall relatively low and showed a limited variability. Thus, the possibility of observing an association

between hyperactive-impulsive behavior and any outcome was very limited in our sample. Future studies examining a possible moderating role of hyperactive-impulsive behavior should target samples with a wider variability in this construct, and specifically include preschoolers at risk for ADHD.

The composition of our sample presents another important limitation: parents in our sample showed a rather high overall educational level, limiting the representativeness of our sample and the generalizability of our findings. In nearly all models conducted in this study, parental level of education was a significant positive predictor of EF performance (expect for inhibition). Further examining what aspects of the families' environments, daily structures or activities might be specifically beneficial for EF development could help to better understand the additional effect that PA might have. Different indirect routes of promoting EF development exist (Diamond, 2012), and collectively examining them in one study could yield more accurate insights into the effects of the single promoting activities. For example, PA might be specifically beneficial for children that receive less other EF promotion.

Conclusion

Our study revealed a negative association between objectively accelerometer measured MVPA and EF measured with the German version of the EF Touch in a sample of 68 German preschoolers. This result pattern contradicted our hypothesis but was in line with another study implementing the same EF measure in US preschoolers by Willoughby et al. (2018). Contradicting their explanation for the unexpected result pattern, we found that this association was not moderated by hyperactive-impulsive behavior. Regarding the separate EF components, MVPA was only negatively related to working memory. When separately examining time spent in different PA intensities as well as parent-reported PA, we found no association with EF. An explorative analysis only revealed a positive association with sedentary behavior. The observational design of our study does not allow directional or causal inferences. Further, the rather low manifestation of hyperactive-impulsive behavior in our sample might have limited the possibility to detect a moderating effect. Future research should specifically include preschoolers at risk of ADHD and include more diverse samples concerning parental educational background. More research is necessary to investigate the role of specific types of PA as well as different sedentary activities for EF development in preschool age.

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Supplementary Material

Additional Statistical Analysis

Since we observed a positive correlation between time spend sedentary and total EF (r = .31, p = .009), we also conducted a multiple regression model with sedentary behavior as predictor and total EF score as outcome. Again, we controlled for age, child gender, BMI, parental level of education, and hyperactive-impulsive behavior (measured with SDQ as in hypothesis testing). All control variables and the predictor were centered on the grand mean.

Results

The multiple regression model examining sedentary behavior (see *Table A2*) revealed a positive association between time spent sedentary and EF (β = 0.34, p = .013). More time spent in sedentary behavior was thus related to better total EF. Concerning the control variables, age (β = 0.39, p = .003) and parental level of education (β = 2.12, p = .031) were positively related to total EF.

Table A2

Association between Sedentary Behavior and Total Executive Function Score

	Est.	CI	*p*
Intercept	**63.20**	**54.63 – 71.77**	**<0.001**
Sedentary Behavior [in %]	**0.34**	**0.07 – 0.60**	**0.013**
Age	**0.39**	**0.14 – 0.63**	**0.003**
Gender (female)	1.58	-2.43 – 5.59	0.434
BMI	-0.51	-1.83 – 0.81	0.441
Parental education	**2.12**	**0.20 – 4.04**	**0.031**
Hyperactivity/Impulsivity	-1.69	-5.82 – 2.43	0.414

Note. N = 65, R^2 = 0.407.

Appendix B: Manuscript 2

Free-Living Physical Activity and Executive Function: A multi-Study Analysis of Age Groups and Times of Day

Eppinger-Ruiz de Zarate, A., Powell, D., Kühnhausen, J., Allan, J. L., Johnstone, A., Crabtree, D. R., Buosi, W., Fyfe, C. L., McMinn, D., McCavour, B., Gawrilow, C., & Stadler, G. (2024). Free-living physical activity and executive function: A multi-study analysis of age groups and times of day. *International Journal of Clinical and Health Psychology*, *24*(1), 100425. https://doi.org/10.1016/j.ijchp.2023.100425

International Journal of Clinical and Health Psychology 24 (2024) 100425

Contents lists available at ScienceDirect

International Journal of Clinical and Health Psychology

journal homepage: www.elsevier.es/ijchp

Free-living physical activity and executive function: A multi-study analysis of age groups and times of day

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ARTICLE INFO

Keywords:
physical activity
accelerometer
cognitive function
ambulatory assessment

ABSTRACT

Background: Executive Function (EF) is a potential mechanism linking physical activity (PA) and mental health. However, evidence regarding the association between free-living PA and EF is limited with mixed results. Across two studies, we examined associations between accelerometer-assessed moderate-to-vigorous PA (MVPA) and facets of EF in different age groups (Study 1) and at different times of day (Study 2).
Method: In Study 1, we tested the association between MVPA and verbal fluency across seven days in 285 participants (children, adults, older adults). In Study 2, we tested between- and within-person associations between MVPA and working memory (afternoon, evening, next morning) across three 18-day bursts in 64 preadolescents.
Results: Study 1 showed no association between MVPA and verbal fluency overall, but there was an interaction by age group: a positive association was evident in older adults only. In Study 2, we observed a positive between-person association between MVPA and subsequent afternoon and next morning working memory, but not within-person. In the evening, MVPA was not related to working memory.
Conclusions: The association between free-living PA and EF differs between age groups and times of day. Future research should consider these factors when examining the association and its role for mental health.

Physical activity and executive function: A multi-study analysis of age groups and times of day

Living a physically active life is of central importance for mental health across the lifespan. For example, physical activity (PA) interventions can prevent depression in the general population across different age groups (Hoare et al., 2021). While PA refers to any bodily movement increasing energy expenditure, moderate-to-vigorous PA (MVPA) is especially effective in the treatment of depression (Schuch et al., 2016).

One possible factor that mediates the link between PA and different mental health aspects (e.g., depressive symptoms) is executive function (EF; Dong et al., 2022): a set of higher order cognitive functions enabling individuals to direct and regulate their cognitions, emotions, and actions

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https://doi.org/10.1016/j.ijchp.2023.100425
Received 21 July 2023; Received in revised form 10 November 2023; Accepted 20 November 2023

in a goal-oriented manner (Barkley, 2001). EF deficits can be observed for example in individuals with depression, and PA presents a promising nonpharmacological intervention to increase EF in this population (Ren et al., 2023). On the neurophysiological level, PA alters brain activity and connectivity, thereby improving EF (Erickson et al., 2015), which could indirectly explain the positive association between PA and mental health. Miyake et al. (2000) postulated the integrative model of EF that describes EF as consisting of one common underlying factor and three distinct components: cognitive flexibility, working memory (WM), and inhibition. EF undergoes a shift in development in preschool age, continuing into young adulthood (Huizinga et al., 2006). The age at which EF peaks and begins to decline depends on the specific EF component but all EF components show decreases in function with age, starting in midlife and progressing into older adulthood (Ferguson et al., 2021). In addition to age, individual characteristics (Kramer & Colcombe, 2018) and external influences also determine EF performance (Dirk & Schmiedek, 2017). EF fluctuates over time (McKinney et al., 2020) and is related to individuals' engagement in effortful behaviours like PA.

Relationship between physical activity and executive function

So far, most research has examined the relationship between PA and EF with interventional study designs (Donnelly et al., 2016). Reviews and meta-analyses report positive effects of PA interventions on EF across the lifespan (Alvarez-Bueno et al., 2017; Colcombe & Kramer, 2003; Donnelly et al., 2016; Verburgh et al., 2014). Ludyga et al. (2016) re-analyzed data from 40 interventional studies across the lifespan and found a small positive effect of PA on overall EF with strongest benefits in preadolescents and older adults. They explained this with higher sensitivity to PA in phases of developmental change.

While results from interventional research point towards a beneficial effect of PA on EF, these findings do not necessarily generalize to free-living PA and its implications for mental health. Yet, research examining the effect of free-living PA on EF is limited (Wickel, 2017). Across the lifespan, reviews suggest a positive link (Cox et al., 2016; Donnelly et al., 2016). Cross-sectional studies showed that objectively-measured total volume of PA was positively related to EF in children (van der Niet et al., 2015), and questionnaire-assessed free-living PA was positively related to EF in young adults (Kamijo & Takeda, 2010) and in older adults (Reas et al., 2019). However, very few studies used accelerometers as an objective and valid measure of free-living PA. Correlations between questionnaire- and accelerometer-derived PA are low-to-moderate (Prince et al., 2008), and differences between measurement methods possibly influence the observed relationship between PA and EF (Syväoja et al., 2014). Thus, more research examining the association between objectively measured free-living PA and EF is needed to better understand the role of an active lifestyle for EF (Donnelly et al., 2016).

Present Research

We present two studies to examine different aspects of the relationship between free-living PA and key facets of EF as secondary analyses of two existing datasets: (1) a large cross-sectional study of verbal fluency (VF) and accelerometer-assessed PA across children, adults, and older adults; and (2) an intensive longitudinal study of spatial WM across different times of day (mornings, afternoons, evenings) and accelerometer-assessed PA in preadolescents.

Study 1

Examining the role of free-living PA for EF across the lifespan is important, because evidence supports a causal positive effect of MVPA on cognitive functions (Cheval et al., 2023) and a longitudinal association between PA and EF, with strongest effects in lifelong active individuals (Reas et al., 2019). Further, findings from studies objectively measuring free-living PA and its relation to EF are mixed across different age groups. In preadolescent children, multiple studies reported no association between accelerometer-measured MVPA and cognitive flexibility (Syväoja et al., 2014; van der Niet et al., 2015), while in young adults, evidence suggests a positive association (Lin et al., 2018). In middle-aged and older adults, a study suggests that as little as ten minutes of MVPA per day were related to better cognitive flexibility (Spartano et al., 2019). The VF test implemented in study 1 is often considered to tap cognitive flexibility (Diamond, 2013) though VF has also been argued to involve a combination of general executive functions (e.g., Gustavson et al., 2019).

Since only a limited number of studies examined the relationship between objectively measured free-living PA and EF (Wickel, 2017), findings are inconsistent across age groups, and studies are conducted in different age groups rather than across multiple age groups, we wanted to examine this association across the lifespan. We hypothesised a positive association between free-living MVPA and VF as a measure of cognitive flexibility in children, adults, and older adults. We followed this up by exploring the interaction of this association by age, expecting to see a more positive association among adults.

Method

Design & Participants

Study 1 pools three datasets from larger projects (Full4Health: (Crabtree et al., 2020); Snapshot: (McMinn & Allan, 2014); StudentProject: (McCavour, 2018)) that all included the same EF task and objective measurement of free-living PA over seven days via accelerometers, resulting in a total sample of 285 participants. The description of each sample can be found in the Appendix.

We applied a minimum wear-time criterion of 4 days of data with at least 6 hours of wear-time per day, including at least one weekend day (Jerome et al., 2009). This led to the exclusion of 36 participants (Full4Health: 31, Snapshot: 2, StudentProject: 3), leaving a final pooled sample for analysis of 249 participants. Of these, 68 were children (under 18 yrs: $M = 11.97$ yrs, $SD = 3.71$ yrs), 144 adults (18-64 yrs: $M = 34.33$, $SD = 13.35$), and 36 older adults (65 yrs or older: $M = 68.6$, $SD = 3.32$). All three projects were approved by the University of Aberdeen Ethical Review Boards (CERB/2012/8/761; CERB/2018/2/1547) or the North of Scotland NHS Research Ethics Committee (12/NS/0007).

Measures

Executive Function. We used the VF test of the Delis-Kaplan Executive Function System (D-KEFS; Delis et al., 2001), including the letter fluency task only. The letter fluency task is a 5-minute task requiring participants to name as many words as they can, in 60 seconds, starting with F, then A, then S. Participants are asked to avoid names, place names, numbers, repetitions, and the same word with different endings (e.g. slow, slowing). Raw scores are converted to scaled scores normed by age and gender, with higher scores reflecting better VF performance.

Physical activity. Free-living MVPA was assessed over seven consecutive days by Actigraph GT3X+ accelerometers (Actigraph, LLC, Fort Walton Beach, Florida) worn on the hip during waking hours. Bodily movements were measured on three axes with a frequency of 30 Hz and epoch length of one minute. For this analysis, Axis 1 counts were converted to minutes of MVPA using validated thresholds for adults (Freedson et al., 1998) and children (Freedson et al., 2005).

General Procedure

After providing written informed (parental) consent, participants were asked to attend the University of Aberdeen to undertake a battery of cognitive tests, which included the D-KEFS letter fluency task.

Children were generally tested in the school setting. Participants were shown how to wear the accelerometer and left the research site wearing it in the correct position. Formal data collection began the next day, and lasted for seven consecutive days. Upon completion, participants returned the devices to the researcher. In Full4Health and Snapshot, all participants had travel costs reimbursed; in StudentProject, participants received a £20 retail voucher plus travel costs.

Statistical Analysis

To test the primary hypothesis, we used hierarchical linear regression to model VF performance as a function of minutes of MVPA, controlling for study number, age, gender, and accelerometer wear-time. MVPA data were heavily skewed, and therefore transformed using a log transformation (Log (MVPA + 1)). To test moderation by age, interactions of MVPA×Age for each age group (children, adults, older adults) were examined using dummy variables. All analyses for Study 1 were conducted in SPSS using $\alpha = .05$ to denote statistical significance. All analyses of this two-study paper were pre-registered, and any deviations can be found in a brief document on Open Science Framework (OSF; https://osf.io/xyvk2/).

Results

Descriptive statistics regarding time spent in MVPA, VF and wear-time can be found in the Appendix (Table A.1). In the linear regression, we observed no significant association between MVPA and VF across the age groups ($B = 0.288$, $SE = 0.800$, $p = .719$, 95% CI: -1.289, 1.865; See Table A.2, Appendix).

Examining the interaction by age group, it was evident that the association in older adults was significantly different to that in children (see Table 1; for full model see Table A.3 in Appendix) with a substantially more positive association in older adults (see Fig. 1).

Discussion

Across different age groups, we found no association between time spent in MVPA and EF as measured by VF. This was unexpected, with previous research suggesting a positive association between objectively measured PA and EF across the lifespan (Cox et al., 2016; Donnelly et al., 2016). After including the interaction with age groups (children, adults, older adults), we only found a positive association between MVPA and VF in older adults. In children and adults, we found no association between MVPA and VF, supporting findings found elsewhere where no association was observed between MVPA and cognitive flexibility (e.g., Syväoja et al., 2014).

However, studies elsewhere looking at more specific age groups give a mixed picture. One study of free-living MVPA and various EF tasks found negative associations across all EF domains in 3-5 year olds (Willoughby et al., 2018); a study in 8-12 year olds found total volume of PA (including MVPA and light activity) was associated with better EF (van der Niet et al., 2015), and various papers suggest robust associations between MVPA and EF in older adulthood (Spartano et al., 2019; Zhu et al., 2017) including with the VF test (Daly, McMinn, & Allan, 2015). In a meta-analysis of moderate aerobic exercise effects on EF, small positive effects were observed for reaction time and accuracy measures (Ludyga et al., 2016) but moderation by age was evident in reaction time measures only: effects were strongest in older adults and preadolescents. Taken together, it appears likely any association is most-relevant in older adults, with some potential for specific effects on EF in children, though it appears not for VF; it is likely that VF captures elements of language proficiency over and above EF that may not yet be fully developed in children (Cohen et al., 1999).

Table 1
Linear Regression examining Verbal Fluency Performance as a Function of MVPA and its Interaction by Age Group

	Est.	SE	p
Constant	**11.289**	**0.927**	**< .001**
Gender (Reference = Male)	**-0.921**	**0.457**	**.045**
Adults (Reference = Children)	0.322	1.022	.748
Older Adults (Reference = Children)	2.180	1.254	.083
MVPA	-2.046	2.430	.314
MVPA * Adults	-0.879	2.284	.701
MVPA * Older Adults	**5.212**	**2.563**	**.043**

Note. MVPA is log-transformed and centered at the grand mean. Study covariates (study number, accelerometer wear-time) omitted, see Table A.3 for full results (Appendix).

To our knowledge, the sample in Study 1 is the largest dataset of its kind with objective and comparable measures of free-living PA and EF across different age groups. Study 1 has some methodological limitations: Firstly, our findings were only correlational. Secondly, we defined VF as a subdomain of EF in line with Diamond (2013) but this categorization is debated in the literature (e.g., Whiteside et al., 2016). When interpreting our findings, it needs to be considered that VF measures assess important core aspects of EF but also capture elements of language processing.

Our results from Study 1 highlight the importance of differentiating between age groups when examining the role of free-living PA for EF, which is supported by both interventional and observational research (Ludyga et al., 2016; Spartano et al., 2019; Syväoja et al., 2014). However, to better understand the association between PA and EF, research should not only consider age but also the time frame on which this relation occurs. Longitudinal evidence suggests positive effects of a lifelong active lifestyle (Reas et al., 2019). Thus, effects could accumulate over the life course, resulting in strongest associations in older adults. Objective measures of PA allow us to examine the association in a more natural setting and in more timely proximity, reflecting the increased variability of free-living PA (as compared to PA interventions).

Study 2

In everyday life, PA and EF vary between and also within individuals over time (McKinney et al., 2020; Turrisi et al., 2021). Considering this variability is important when transferring results from interventional studies to a more natural setting. Findings regarding the relation between objectively-measured overall PA levels and WM performance are mixed: one study reported that preadolescents with low PA levels showed significantly worse WM accuracy (Zhu et al., 2022), while other evidence suggests no association between MVPA levels and preadolescents' WM (Mücke et al., 2018; van der Niet et al., 2015). Insufficient control of confounding variables (e.g., general cognitive abilities; Hsieh et al., 2018), or of the variability in PA (Migueles et al., 2021) could explain null-findings and mixed results.

Previous research has shown that the effect of free-living PA differs depending on the investigated time interval: while one study reported beneficial effects of PA for same-evening affect (Haas et al., 2017), another study found no association with next-morning affect (Hachenberger et al., 2023). However, only a limited number of studies have considered the variability of PA when examining its role for EF. First evidence suggests that activity-rest-patterns – rather than overall PA levels – are related to WM performance in preadolescents (Migueles et al., 2021). Ambulatory assessment studies are particularly well-suited to capture such variability and different time scales, as they repeatedly measure individuals' behaviour, permitting the separation of effects found between individuals (between-person) from those found within individuals over time (within-person). To our knowledge, only one ambulatory assessment study investigated MVPA and WM in preadolescents (Trevillion et al., 2022): over 14 days, 35 preadolescents wore an accelerometer and performed a WM task twice per school day. Higher levels of MVPA on the prior day were related to lower WM on the following day, but there was no association with MVPA in the two hours

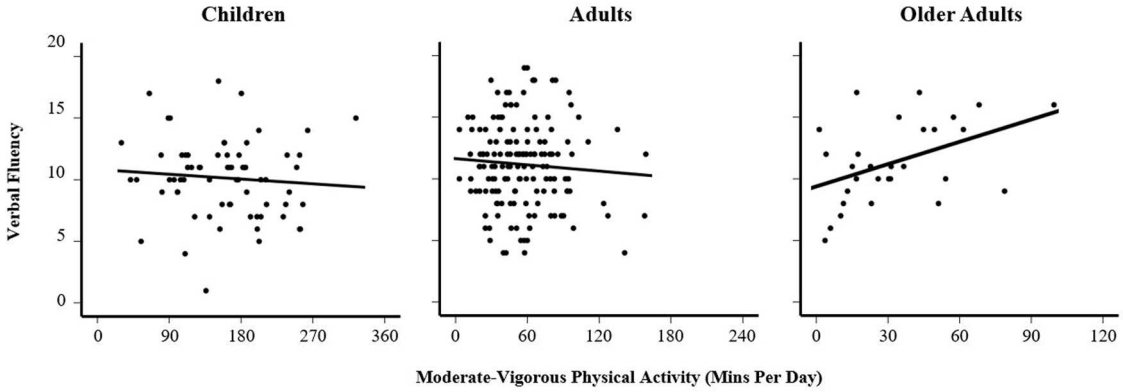

Fig. 1. Association between Physical Activity and Verbal Fluency across different Age Groups

prior to WM assessment. These findings support a within-person relation between prior day MVPA and WM but not within the same day, highlighting the importance of examining the association between PA and EF on different time scales. However, Trevillion et al. examined a relatively small sample and collected data only twice a day for two weeks. Studies with larger sample sizes and more measurement occasions over a longer time period are necessary to better understand the associations between free-living PA and EF within and between individuals in everyday life and on different time scales.

Thus, in Study 2, we conducted an ambulatory assessment study to examine the relationship between objectively measured free-living PA and WM in preadolescents on three different time scales. During three 18-day data collection bursts, preadolescents completed a visual WM task in the morning, afternoon, and evening. This is a novel examination testing the role of PA at different times across the entire day over the course of one year, allowing us to draw conclusions about the variability of the association between PA and EF but also the stability of the examined effects. We used WM as a measure of EF in Study 2, because a recent meta-analysis (Alvarez-Bueno et al., 2017) suggested that WM might be especially sensitive to PA in youth. We expected that preadolescents' MVPA would be positively related to their WM accuracy on the between- and within-person level at all times of day.

Methods

Participants

Preadolescents (10-13 yrs) were recruited at schools in Southwest Germany. Over the course of the study, 74 participants took part, but only 64 participants wearing an accelerometer were considered for this analysis (age: $M = 10.75$ yrs, $SD = 0.49$ yrs[1]; 26 male, 38 female). Due to dropouts between the measurement bursts, 15 participants were newly recruited before the second burst (participation in 1 burst $n = 22$, in 2 bursts $n = 22$, in 3 bursts $n = 20$).

Procedure

Study 2 was part of the AttentionGO project implementing ambulatory assessment. It was funded by the German Research Foundation (project number GA 1277/9-1) and approved by the ethics committee of the German Society for Psychology (CG 102018_amd_112013). Recruitment in schools was approved by the Ministry of Culture, Youth, and Sport in Baden-Württemberg, Germany (file number 31-6499.20/1087). Data were collected in three separate 18-day measurement bursts approximately six months apart (Burst 1: November-December 2017; Burst 2: April-July 2018; Burst 3: November-December 2018).

At the start of each burst, children received smartphones and accelerometers. For each participant, one parent took part in a telephone interview (approx. 1 hr). During the 18 days, the smartphones rang three times a day for data collection and could not be turned on for another purpose. After ringing, children had 30 minutes to perform a spatial WM task. The time points all lay outside school hours: in the morning, afternoon, and evening. The exact times were individually agreed on with the parents at the beginning of each burst with possible differentiation between weekdays and weekends.

Participation was compensated with a 40-euro voucher for a chosen family activity (e.g., zoo visit) after each burst. Further, children received small presents and information about their PA.

Material

Daily Measures

Executive Function. Participants completed a spatial WM task (Dirk & Schmiedek, 2016). They were presented with a matrix divided into 16 equal squares. Depending on the difficulty level, two (Load 2) or three (Load 3) virtual monsters were positioned on these squares and presented for 3000ms, followed by the presentation of the empty matrix for 250ms. After this, arrows appeared indicating in which direction the monsters moved. Each arrow was presented for 1500ms and followed by an inter stimulus interval (ISI) of 250ms. Two arrows were presented in Load 2 and, accordingly, three in Load 3. Finally, children indicated the monsters' new positions (2000ms) and received feedback on accuracy after an ISI of 200ms. Children performed four trials of Load 2 followed by four trials of Load 3. In total, the task took approximately eight minutes.

As a measure for WM, accuracy was assessed in percentage. We only included Load 3 because of observed ceiling effects in Load 2. Accuracy was aggregated over the three answers within each trial of Load 3, and then averaged over all four trials of Load 3. Thus, WM-accuracy scores were computed for 54 measurement occasions per burst (3 per day for 18 days) and participant.

Physical Activity. Participants wore an Actigraph GT3X+ on the hip of their non-dominant side during waking hours, with a frequency of 30 Hz and epoch length of 15 seconds. Axis 1 counts were converted to minutes of MVPA using validated thresholds (Evenson et al., 2008) and aggregated over one hour. Days with a wear-time of less than six hours were excluded (Jerome et al., 2009).

Background Measures

General cognitive abilities. We assessed general cognitive abilities through Raven's Standard Progressive Matrices (Horn, 2009) at the end

[1] For one subject, no age data was available. This child's age was estimated for the models.

of the first burst each child participated in and calculated the sum score.

Demographic Data. Children's age and gender were collected in the parental interview.

Data Analysis

All analyses for Study 2 were conducted with the statistical software R version 4.1.3 using $\alpha = .05$ to denote statistical significance. To test our hypotheses, we ran three multilevel linear regression models predicting WM performance in the (a) afternoon, (b) evening, and (c) next morning. Within the same day (a, b), PA was operationalised as hours spent in MVPA between 6am and the minute before the respective WM assessment. In the lagged analysis (c), we considered hours spent in MVPA between 6am and 11pm on the prior day. To distinguish between-person from within-person effects, we included two variables in the model: each child's mean hours spent in MVPA averaged across all bursts and centred on the grand mean to test the link of between-person differences in MVPA and EF; daily fluctuations in MVPA from 6am until the minute before the respective WM assessment at each study day centred around each child's person mean to test the within-person link between fluctuations in MVPA and EF. To account for possible training effects in the WM task, we included a linear time trend of study day (range 0-1) and dummy-coded variables representing the burst. We controlled for weekend, gender and wear-time (in hrs), age at Burst 1 and general cognitive abilities (centred on grand mean). We estimated random effects for the intercept, the within-person effect of MVPA, study day, the continuous autocorrelation of Level 1 residuals, and correlations between random effects. The equations describing the full models can be found in the Appendix.

Results

Descriptive Results. Descriptive statistics regarding wear-time, time spent in MVPA and WM performance can be found in the Appendix (Tables A.4, A.5). MVPA varied across bursts (in mins; Burst 1: $M = 48.16$, $SD = 29.01$; Burst 2: $M = 60.97$, $SD = 46.96$; Burst 3: $M = 47.41$, $SD = 25.39$) with highest MVPA levels in Burst 2, and it differed between gender (in mins; girls: $M = 46.38$, $SD = 31.06$; boys: $M = 60.87$, $SD = 40.33$) with higher MVPA levels in boys. WM performance differed between bursts (in percentage; Burst 1: $M = 56.32$, $SD = 29.29$; Burst 2: $M = 60.72$, $SD = 29.48$; Burst 3: $M = 65.53$, $SD = 26.99$). Girls ($M = 62.68$, $SD = 28.70$) had higher scores, on average, than boys ($M = 56.12$, $SD = 29.09$) across all times of day and bursts.

Multilevel Analyses. The results of the multilevel models concerning the hypotheses as well as significant control variables are reported in Table 2 (for full model see Table A.6 in Appendix), and between-person associations are represented in Fig. 2.

Afternoon Analysis. We found a significant positive between-person relationship between MVPA and afternoon WM performance ($\gamma_{01} = 24.90$, $p = .035$). This did not change across the bursts, implying a stable positive between-person association. However, we did not find this association on the within-person level ($\gamma_{10} = 0.01$, $p = .999$). We observed a significant increase in WM between bursts (Burst 2: $\gamma_{30} = 5.59$, $p = .011$; Burst 3: $\gamma_{40} = 8.92$, $p < .001$).

Evening Analysis. We found no between-person association between MVPA and evening WM performance ($\gamma_{01} = 12.39$, $p = .116$), and, after including autocorrelation, the negative within-person association failed to reach significance ($\gamma_{10} = -5.20$, $p = .057$). Again, we found a significant increase in evening WM between bursts (Burst 2: $\gamma_{30} = 4.51$, $p = .036$; Burst 3: $\gamma_{40} = 9.98$, $p < .001$).

Morning Analysis. We observed a significant positive between-person relationship between prior day MVPA and morning WM performance ($\gamma_{01} = 17.16$, $p = .038$) that did not significantly change over the bursts. On the within-person level, we did not find an association ($\gamma_{10} = -0.21$, $p = .942$). Morning WM significantly increased from Burst 1 to Burst 3 ($\gamma_{40} = 8.69$, $p < .001$).

Discussion

In Study 2, we found stable positive between-person associations between MVPA and WM in the afternoon and morning, in line with previous research (e.g., Hsieh et al., 2018). The design of Study 2 expands previous findings through information about the stability of the observed effects, as the relation between MVPA and EF was stable across a longer period in preadolescence and different seasons (Burst 1, 3: winter; Burst 2: summer). In the evening, we did not find a between-person association between MVPA and WM performance, contradicting our hypothesis but in line with some previous research (e.g., van der Niet et al., 2015). In children, EF performance is typically not measured in the evening. Thus, findings from other studies (e.g., Trevillion et al., 2022) might not be applicable to the evening WM assessment in our study. Before the evening assessment, daily structures and routines might have strongly varied between individuals, influencing the relationship between MVPA and WM. Hence, future studies

Table 2
Physical Activity (MVPA in hrs) predicting Working Memory (in %) at different Times of Day while controlling for Study Day, Weekend, Wear-Time, Gender, Age, and General Cognitive Abilities

Fixed Effects			Afternoon Est.	SE	Evening Est.	SE	Next Morning Est.	SE
Burst 1 (Reference)								
	Starting point	γ_{00}	**42.26**	3.85***	**48.74**	3.76***	**49.47**	3.95***
	MVPA, between-person effect	γ_{01}	**24.90**	11.52*	12.39	7.77	**17.16**	8.08*
	MVPA, within-person effect	γ_{10}	0.01	3.84	-5.20	2.72	-0.21	2.89
Difference in Burst 2 vs. 1								
	Starting point	γ_{30}	**5.59**	2.19*	**4.51**	2.15*	3.03	2.25
	MVPA, between-person effect	γ_{31}	-2.35	8.35	-2.46	6.46	-1.51	6.72
	MVPA, within-person effect	γ_{50}	-3.22	4.33	4.42	3.20	-0.78	3.43
Difference in Burst 3 vs. 1								
	Starting point	γ_{40}	**8.92**	2.41***	**9.98**	2.34***	**8.69**	2.39***
	MVPA, between-person effect	γ_{41}	-8.06	9.10	-6.79	6.75	-6.63	6.89
	MVPA, within-person effect	γ_{60}	-2.41	6.35	6.08	4.59	-1.23	4.90
Adjustment variables								
	Weekend	γ_{80}	0.48	2.23	**-3.73**	1.90	-0.78	2.03
	Gender (female)	γ_{03}	**13.76**	4.93**	**10.75**	4.60	**13.65**	4.89**
	Age	γ_{02}	-2.48	2.19	-3.24	2.13	**-4.84**	2.24*
	General cognitive abilities	γ_{04}	**6.95**	2.24**	**5.51**	2.15*	**6.28**	2.27**
$N_{observations}$			1060		1262		992	
$N_{participants}$			63		64		63	

Note. *** $p < .001$, ** $p < .01$, * $p < .05$. Study covariates (study day, accelerometer wear-time) omitted, see Table A.6 for full results (Appendix).

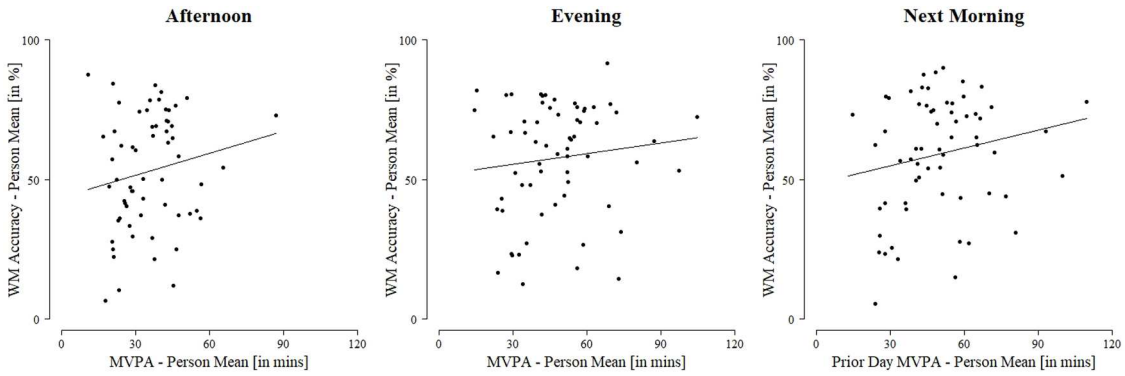

Fig. 2. Between-Person Association between Physical Activity per Day (Person Mean) and Working Memory (Person Mean) across different Times of Day

examining the role of PA for evening WM should assess such contextual variables.

On the within-person level, we found no associations between MVPA and WM at any time of day. This contradicted our hypotheses but was somewhat in line with findings from the ambulatory assessment study by Trevillion et al. (2022) which found that MVPA in the two hours prior to WM assessment was not related to WM. Regarding prior day MVPA, they reported a negative association with WM while we found no association. Inconsistencies between the two studies might be explained through methodological aspects (e.g., different WM tasks). Contradicting our hypothesis, we observed a trend towards a negative association in the evening. Increased fatigue in the evening after more PA on the respective day (Haas et al., 2017) might negatively influence EF performance and explain this result pattern.

As in Study 1, our findings were only correlational. Still, the design of Study 2 offers considerable benefits yielding novel insights: As an ambulatory assessment study, Study 2 ensures a high ecological validity and reflects variability occurring in everyday life. This enables us to better understand the *real-life* and *real-time* association between individuals' PA and their EF. Further, the examination of preadolescents' WM in the evening granted us novel insights into the association between PA and EF beyond previous examinations (e.g., Trevillion et al., 2022). The association between PA and EF in the evening varied from the morning and afternoon associations, and more research is necessary to better understand why the association differs between times of day.

General Discussion

The two studies presented in this paper offer an overarching examination of the relationship between objectively measured free-living PA and EF across the life span. The aim was to better understand the relationship between PA and EF in everyday life, by examining the relation in different age groups (Study 1) and on different time scales (Study 2). Study 1 revealed differences in the relationship between age groups: in line with previous findings (Ludyga et al., 2016), we observed strongest associations in older adults (positive association). In Study 2, we focused on preadolescents as an age group with limited previous research findings, and found differences between time of assessment: while we found no association in the evening, MVPA was positively related to subsequent WM in the afternoon and next morning between individuals. A key finding of Study 2 was that these associations were all stable across three measurement bursts spanning one year. The observed differences in the relationship between PA and EF in children may be explained with WM (Study 2) being more sensitive to PA in children than VF (Study 1; Alvarez-Bueno et al., 2017).

It is a strength of our multi-study paper that we employed objective measures of PA (accelerometer) and EF (objective tests of VF and WM), expanding previous research that often relied on interventional study designs (Wickel, 2017) or questionnaire-assessed PA (Donnelly et al., 2016). For Study 1 we examined VF, as the VF Test (Delis et al., 2001) was previously scaled across the lifespan. However, VF possibly captures language proficiency yet not fully developed in children (Cohen et al., 1999), thereby underestimating the association between PA and EF. Thus, in Study 2, we examined WM as a specifically sensitive measure in children (Alvarez-Bueno et al., 2017), although somewhat limitting the comparability between the two studies.

Despite the advantages of objectively measured PA, investigations of qualitative characteristics of PA and their relation to EF could help explain inconsistent research findings (van der Niet et al., 2015). Thus, future research could combine objective measures of PA with questionnaires. Further, our findings from Study 2 highlight the importance of employing more ambulatory assessment studies in the future to better understand the relation between PA and EF between and within individuals but also on different time scales. It could be especially interesting for future studies to examine the role of PA for evening EF. Ambulatory assessment studies should also be implemented in different age groups - especially in those with fast developmental changes (e.g., older adults). Future work should further implement comparable EF measures across the lifespan (Study 1) to increase comparability between different age groups.

Our findings implicate that free-living PA is of high relevance for EF, which, again, is relevant for individuals to engage in health behaviours (Dong et al., 2022). EF are closely linked to individuals' mental health (e.g., depressive symptoms), and PA could be a promising solution to increase EF and therefore improve diverse mental health aspects (Ren et al., 2023). Investigating the importance of a physically active lifestyle is becoming increasingly important, and our paper helps generate hypotheses for future studies regarding differences between age groups as well as time of day. More research is needed to fully understand the relation between PA and EF in everyday life, and the role they can play for mental health.

Funding

This paper was supported by the Scottish Government, Rural and Environmental Science & Analytical Services (RESAS) division. The Full4Health project was funded by the European Union's Seventh Framework Programme FP7-KBBE-2010-4 under grant agreement No: 266408. Authors from the University of Aberdeen, Rowett Institute gratefully acknowledge financial support from the Scottish Government as part of the RESAS Strategic Research Programme at the Rowett Institute. The AttentionGO project was supported by the Deutsche Forschungsgemeinschaft (GA1277/ 9-1). Gertraud Stadler gratefully acknowledges financial support from the Chancengleichheits-Programm. We acknowledge support from the Open Access Publication Fund of the University of Tübingen.

CRediT authorship contribution statement

Anne Eppinger-Ruiz de Zarate: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Daniel Powell:** Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **Jan Kühnhausen:** Conceptualization, Data curation, Methodology, Writing – review & editing, Formal analysis. **Julia L. Allan:** Conceptualization, Writing – review & editing, Funding acquisition, Methodology. **Alexandra Johnstone:** Writing – review & editing, Funding acquisition. **Daniel R. Crabtree:** Writing – review & editing, Investigation. **William Buosi:** Writing – review & editing, Investigation. **Claire L. Fyfe:** Writing – review & editing, Investigation. **David McMinn:** Data curation, Writing – review & editing, Investigation, Methodology. **Brett McCavour:** Writing – review & editing, Investigation. **Caterina Gawrilow:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing, Project administration. **Gertraud Stadler:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Formal analysis.

Declaration of Competing Interest

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

Acknowledgments

The authors wish to thank all participants (and parents) for taking part in the studies. Additionally, we want to thank Merle Reuter and Ulrike Schwarz for their help in data collection and preparation of the AttentionGO project. We also thank the student assistants for their support in data collection in all studies. Further, we thank Patrick E. Shrout for his expert advice and valuable feedback on the first draft of the manuscript.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijchp.2023.100425.

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Appendix C: Manuscript 3

Well-Being of Adolescents During the COVID-19 Pandemic: Ambulatory Assessment of Physical and Sport Activity, Social Contacts, and Screen Time.

Eppinger Ruiz de Zarate, A., Thiel, A., Sudeck, G., Dierkes, K., John, J. M., Nieß, A. M., & Gawrilow, C. (2023). Well-being of adolescents during the COVID-19 pandemic: Ambulatory assessment of physical and sport activity, social contacts, and screen time. *Zeitschrift Für Psychologie*, *231*(2), 83–92. https://doi.org/10.1027/2151-2604/a000518

Original Article

Well-Being of Adolescents During the COVID-19 Pandemic

Ambulatory Assessment of Physical and Sport Activity, Social Contacts, and Screen Time

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Abstract: During the COVID-19 pandemic, implemented social distancing measures led to behavioral changes and decreased well-being in adolescents. The aim of this study was to examine the relation between daily behaviors (physical and sport activity, social contacts, screen time) and adolescent well-being. For this, we conducted a 28-day ambulatory assessment study. Daily data of 125 German adolescents (11–20 years) were collected every evening through self-report and analyzed with multilevel models. Between and within individuals, physical activity was positively related to well-being and screen time was negatively related to well-being. Social contacts were positively related to well-being within individuals. Explorative analyses revealed differences between sport activity contexts (sports club, leisure time, school), and between in-person and digital social contacts. Our findings suggest that physical activity and in-person social contacts are positively related to adolescent well-being and should, thus, be enabled during the pandemic. Furthermore, the role of screen time should be considered in health promotion.

Keywords: COVID-19 pandemic, adolescent well-being, physical activity, social contacts, screen time

People's daily lives and behaviors were affected by social distancing rules, lockdowns, and school closures implemented during the COVID-19 pandemic. Warnings about negative effects of distancing rules were raised – especially for youth as they were affected in a particularly crucial phase of development (Fegert et al., 2020). In this context, Thiel et al. (2021) speak of a COVID-19 paradox of infection prevention: While social distancing protects against infections, the people to be protected are socially isolated, put under enormous psychological strain, and might suffer a decline of physical health.

Accordingly, a growing body of research reported decreased well-being (Meherali et al., 2021) and increased mental health problems (Racine et al., 2021) in adolescents during the pandemic. Most studies reported cross-sectional data, but an increasing number of longitudinal studies have been published. Those examining well-being before and after the pandemic onset in healthy German adolescents reported decreases (Ravens-Sieberer et al., 2021; Vogel et al., 2021). However, longitudinal data considering possible impacting factors in youth are still scarce.

First findings suggest that decreases in adolescent mental health were related to the perceived pandemic-related impact on lifestyle (De France et al., 2022). Thus, it is important to examine the effect of lifestyle changes on adolescent well-being and to differentiate which daily behaviors might pose as risk or resilience factors.

Physical and Sport Activity

Among other daily behaviors, physical activity (PA) and sport activity (SA) have been discussed (e.g., Cosma et al., 2021). While PA denotes any bodily activity resulting in increased energy expenditure, SA constitutes a subtype of PA characterized by clear aims (e.g., performance, fitness, health) and a structured setting. During the pandemic, PA and SA levels decreased globally (Kharel et al., 2022).

Scientific evidence suggests that these declined PA or SA levels were negatively related to adolescent well-being (Cosma et al., 2021; Marckhoff et al., 2022). First findings comparing PA levels during different pandemic waves in Germany suggest that PA levels did not increase from the pandemic onset to the second lockdown (January 2021; Poulain et al., 2022). Hence, examining the role of PA and SA for adolescent well-being in different pandemic phases is important to better understand the relation and draw conclusions for future phases.

Moreover, it is important to consider the context of PA and SA. Sports club participation during the pandemic was positively related to well-being (Basterfield et al., 2022). School-based fitness interventions are believed to aid adolescent well-being and diminish negative outcomes of pandemic-related declined PA levels (Cataldi et al., 2021). Yet, no studies have jointly examined the effects of PA and SA in different contexts on adolescent well-being during the pandemic.

Social Contacts

Another aspect of daily life highly affected by the pandemic were social contacts. In adolescence, peer social contacts play an important role for well-being (Brown & Larson, 2009) and a decreased number of social contacts poses a risk factor for loneliness (Victor & Yang, 2012). Studies before the pandemic showed that adolescents' isolation from peers and loneliness was negatively related to well-being (Loades et al., 2020). After the pandemic onset, the number of social contacts in youth decreased (Vogel et al., 2021) and loneliness was related to more mental health problems (Cooper et al., 2021). Thus, it is important to further observe the effect of limited social contacts on adolescent well-being.

With social isolation, the use of social media and online platforms has become increasingly important to stay in contact (Pandya & Lodha, 2021). Consequences for adolescent well-being have often been discussed as research prior to the pandemic suggests a negative association between social media use and well-being (Orben, 2020). However, in the pandemic context, this association is not yet fully understood (Pandya & Lodha, 2021).

On the one hand, digital social contacts can positively impact well-being through support and connection (Popat & Tarrant, 2022). Espinoza and Hernandez (2022) observed that only in adolescents with limited digital social contacts, perceived negative pandemic-related changes were related to more loneliness. On the other hand, a negative impact of digital social contacts on youth mental health has been reported (Cooper et al., 2021). One study found that in-person contacts could not be replaced digitally (Jusienė et al., 2022). Hence, differentiating between in-person and digital social contacts is important when examining their role for adolescent well-being.

Screen Time

Another currently discussed daily behavior is screen time (e.g., Nagata et al., 2022). It has often been reported as a risk factor for well-being in youth. Prepandemic evidence consistently suggested a negative association between leisure time screen use and mental health (Hoare et al., 2016). During the pandemic, studies repeatedly observed increases in youth screen time (Kharel et al., 2022).

Negative associations between this pandemic-related increase in screen time and well-being have globally been reported in adolescent samples (Cosma et al., 2021; Nagata et al., 2022). Longitudinal studies found more screen time to be related to worse mental health (Rosen et al., 2021). This indicates that screen time poses a risk factor for adolescent well-being, but the relation in the pandemic context should be further investigated (Pandya & Lodha, 2021).

Since mental health was found to be related to perceived pandemic-related lifestyle change (De France et al., 2022), examining the effects of changed daily behaviors for adolescents' well-being is of particular importance. For instance, Pandya and Lodha (2021) argue that negative effects of screen time on well-being might be reduced during the pandemic as it presented the best possibility for social interactions. So far, most research examining the relation between daily behaviors and adolescent well-being has used cross-sectional study designs and relied on comparisons between individuals. To study changes within individuals, ambulatory assessment studies are the method of choice.

Ambulatory Assessment During the COVID-19 Pandemic

Ambulatory assessment studies repeatedly measure behavior in real-life situations, ensuring high ecological validity. They allow separating effects found between individuals (between-person) and effects found within individuals over time (within-person). So far, only a limited number of ambulatory assessment studies have examined PA, social contacts or screen time, and their relation to well-being in adolescents during the pandemic. Regarding screen time, one study collected monthly data in adolescents between autumn 2020 and spring 2021 (Camerini et al., 2022). Between individuals, higher screen time was related to more mental health problems, while within individuals, no relation was observed. This highlights the

importance to differentiate between-person from within-person associations. To our knowledge, only one ambulatory assessment study examined all three daily behaviors of interest in adolescents from November 2020 to April 2021 (Munasinghe et al., 2020): After the implementation of pandemic-related restrictions, PA levels decreased and adolescents spent more time alone, while screen time increased. Furthermore, the authors observed a decline in adolescents' happiness.

Purpose of the Study

The aim of our study was to investigate the relation between daily PA, SA, social contacts, screen time, and well-being in adolescents over four weeks in the year after the COVID-19 pandemic onset in a small city in Southwestern Germany. In the first German lockdown (March–May 2020), amateur SA in groups and sports clubs was prohibited, sport facilities and schools were closed, and social gatherings were only allowed in small groups. Restrictions in all domains were loosened between June and December 2020. After this, in Southwestern Germany, amateur SA was only allowed for individuals or two people and strict social distancing rules applied again. Starting in March 2021, SA without physical contact was allowed but depended on the regional number of infections, and SA in schools was only allowed for exam preparation. In June 2021, the restrictions were loosened allowing SA in schools outdoors, SA in bigger groups, and SA with physical contact. Yet, rules for SA in sports clubs and leisure time depended on the regional number of infections.

Thus, at the time point of our study, adolescents were again more flexible in their daily routines, as SA was allowed in sports clubs, leisure time, and school, and social distancing rules were loosened. Different pandemic-related effects on youth's well-being have been reported depending on the pandemic phase (Widnall et al., 2022), and our study enhances the scientific understanding of the relation of daily behaviors and adolescent well-being over the multi-annual pandemic trajectory. We aimed to examine possible beneficial effects of daily behaviors enabled again at that time point in Germany (e.g., SA in sports clubs) and chose an ambulatory assessment study design to differentiate between-person from within-person relations.

Based on previous findings, we hypothesized the following associations for both levels (between-, within-person): (1) We expected total PA (including SA) to be positively related to adolescent well-being. (2) We expected the number of overall social contacts (in-person and digital) to be positively related to well-being. (3) We hypothesized screen time to be negatively related to well-being. We further aimed to exploratively examine (A) if there are inter-relations between these daily behaviors, (B) if SA in different contexts (sports club, leisure time, school) is differently related to well-being, and (C) if in-person social contacts are more positively related to well-being than digital social contacts.

Methods

Sample and Procedure

Adolescents were recruited at secondary schools in Tübingen (Southwestern Germany) and in regional sports clubs. Between June and August 2021, a total of 131 adolescents agreed to participate in the study. Only data of participants who completed at least one daily questionnaire were considered for this study. Thus, the final sample size consisted of 125 participants (61% female) aged between 11 and 20 years (M = 14.79, SD = 1.58). Study participation started individually as soon as postal informed consent by parents and adolescents reached the study personnel. All data were collected through online questionnaires using the software SoSci Survey (Leiner, 2019).

First, participants filled out a baseline questionnaire (15–20 min) assessing among others sociodemographic data. Starting on the next day, participants were asked to fill out a short daily questionnaire (5 min) every evening for 28 consecutive days (see the Material section). Participants received the link to the daily questionnaire every evening at 8 p.m. optionally via text message or e-mail, and it could be filled out until 1 a.m. of the next day. After the 28 days, participants were asked to fill out a follow-up questionnaire (10 min). Study participation was voluntary and could be ended at any time without disadvantages for participants. Every adolescent filling out at least half of the questionnaires participated in a lottery of prizes (e.g., visit of a famous German TV show, book vouchers). The study was approved by the ethics committee of the University of Tübingen (May 19, 2021) and the regional board of Tübingen.

Material

The complete questionnaires (baseline, daily, follow-up) and information and interpretation of reliabilities of the relevant scales are provided in the Electronic Supplementary Material 1 (ESM 1).

Daily Measures

To assess *daily psychological well-being*, we adapted four items of the *Short Form-36 Health Survey* (Bullinger et al.,

1995) and two items from the *WHO-5 questionnaire of well-being* (Brähler et al., 2007) for the daily context. Participants answered on a 6-point Likert scale (1 – *never* to 6 – *always*; e.g., "How often did you have a lot of energy today?"). The mean score was calculated, with higher values indicating better well-being.

Daily PA and SA were assessed through the German *Motoric Activity Module PA-Questionnaire* (*Motorik-Modul Aktivitätsfragebogen*; Schmidt et al., 2016). Duration of daily PA was assessed in minutes with two adapted items (e.g., "How many minutes did you walk by foot today?"). Duration of SA in minutes was assessed in three different contexts with each one adapted item: sports club, leisure time, and school. PA and SA were transformed to 10-min units. Total PA was operationalized as the sum of time spent in PA and SA across all contexts.

We assessed the number of *daily social contacts* outside of school with two self-developed items, one for in-person (e.g., "Today, how many friends did you meet personally outside of school and spend time with them?") and one for digital social contacts (e.g., through social media). The number was a standard deviation on the between-person *SD*.

We assessed *daily screen time* with four items of the *Health Behavior in School-aged Children questionnaire* (Ottova et al., 2012; e.g., "How many hours today did you spend looking up for information on the internet, browsing the internet?"). Participants answered on a scale from 1 – *not at all* to 8 – *5 h or more*. Following previous analyses (Iannotti et al., 2009), we converted the time indicated by participants to numerical values (in hrs) and computed a sum score.

To assess *days spent in quarantine*, we adapted one item from the *COVID-19 in German Competitive Sports prospective multicenter cohort study* (Niess et al., 2022) for the daily context (i.e., "Did you spend today in quarantine?").

Baseline Measures

We assessed *sociodemographic data* at baseline with self-developed items. For this article, only sex and age will be considered.

Data Analysis

All analyses for the current work (including explorative analyses) were conducted with the statistical software R version 4.1.3 and pre-registered (https://aspredicted.org/blind.php?x=2KN_K1B, submission: March 16, 2022). All predictors were centered around the grand mean (between-person) and the personal mean (within-person). In all models, the dependent variable was daily well-being, and we controlled for continuous autocorrelation of level 1 residuals as well as sex, age, and days spent in quarantine. In addition to the pre-registered variables, we controlled for study day.

All directional hypotheses (1, 2, 3) were tested in one multilevel model including following variables: On level 2, each adolescent i's mean time of total PA (γ_{01}), mean number of social contacts (γ_{02}), and mean screen time (γ_{03}) were included to account for between-person effects. On level 1, total PA (γ_{10}), social contacts (γ_{20}), and screen time (γ_{30}) on day t were added to consider within-person effects. We controlled for study day (γ_{40}; range = 0–27), school day (γ_{50}; dummy-coded: 0 = *weekend/holiday*, 1 = *school day*), and days spent in quarantine (γ_{60}; dummy-coded: 0 = *no*, 1 = *yes*) on level 1 and for sex (γ_{04}; dummy-coded: 0 = *male*, 1 = *female*) and age (γ_{05}; centered on grand mean) on level 2. Random effects were estimated for intercept (υ_{oi}) and within-person effects of total PA (υ_{1i}), social contacts (υ_{2i}), and screen time (υ_{3i}). Correlations between random effects were estimated. The following equation 1 describes the full model:

$$\begin{aligned}\text{Well-Being}_{ti} = {} & \gamma_{00} + \gamma_{01} \cdot \text{total PA\_BP}_i \\ & + \gamma_{02} \cdot \text{social contacts\_BP}_i \\ & + \gamma_{03} \cdot \text{screen time\_BP}_i \\ & + (\gamma_{10} + \upsilon_{1i}) \cdot \text{total PA\_WP}_{ti} \\ & + (\gamma_{20} + \upsilon_{2i}) \cdot \text{social contacts\_WP}_{ti} \\ & + (\gamma_{30} + \upsilon_{3i}) \cdot \text{screen time\_WP}_{ti} \\ & + \gamma_{04} \cdot \text{sex}_i + \gamma_{05} \cdot \text{age}_i \\ & + \gamma_{40} \cdot \text{study day}_{ti} + \gamma_{50} \cdot \text{school day}_{ti} \\ & + \gamma_{60} \cdot \text{quarantine}_{ti} + \upsilon_{oi} + \varepsilon_{ti} \end{aligned} \quad (1)$$

For the explorative analysis A investigating inter-relations between the daily behaviors, we expanded the presented model with between- and within-person interactions between the daily behaviors. The explorative Hypotheses B and C were tested in separate sequentially constructed models that we compared using the likelihood ratio to specify the best-fitting model. The models for the explorative analyses are described in ESM 2. All models were calculated using maximum likelihood estimation and $\alpha = .05$.

Results

Descriptive Results

With 125 participants, a total of 3,500 daily observations would be possible. Participants completed 2,464 daily questionnaires, resulting in a compliance rate of 70%

Table 1. Descriptive statistics for adolescent well-being, total PA, PA and SA in different contexts, social contacts (overall, in-person, digital), and screen time across all 28 study days

	Between-person			Within-person			
Variable	*M*	*SD*	Range	M_{ISD}	*SD*	Range	ICC
Well-being[a]	4.27	0.74	2.12–5.88	0.51	0.22	0.00–1.29	0.62
Total PA[b]	12.65	6.72	1.44–40.86	8.55	4.52	1.07–33.95	0.27
SA – sports club	1.99	2.11	0.00–10.96	3.35	2.60	0.00–13.01	0.15
SA – leisure time	2.75	4.03	0.00–30.00	3.64	2.96	0.00–12.73	0.26
SA – school	0.82	1.22	0.00–9.71	2.28	2.45	0.00–11.27	0.08
PA	7.12	3.79	1.44–20.37	4.86	3.34	0.35–21.21	0.27
Social contacts	5.01	4.50	0.14–36.68	3.58	2.67	0.00–14.72	0.41
In-person	2.07	1.62	0.00–7.33	2.69	2.07	0.00–11.13	0.12
Digital	2.93	3.80	0.00–34.88	1.78	1.87	0.00–12.20	0.62
Screen time[c]	2.65	1.49	0.00–8.00	1.22	0.68	0.00–4.13	0.55

Note. *M* = unstandardized mean, *SD* = *SD*, M_{ISD} = mean intraindividual *SD*, ICC = intraclass correlation coefficient. [a] Theoretical range 1–6 (higher levels indicate better well-being). [b] Duration of PA and SA transformed to 10-min units. [c] Screen time in hrs.

(*SD* = 25; range = 4–100). In our study, the likelihood of missing values decreased by 5% with each year of age (OR = 0.95, 95% CI [0.93, 0.97]) and increased by 4% with each study day (OR = 1.04, 95% CI [1.03, 1.04]). Missing values were 30% less likely in girls compared with boys (OR = 0.70, 95% CI [0.65, 0.75]).

At baseline, only 10% of participants (n = 12) reported spending at least 60 min in moderate-to-vigorous PA every day of the week prior to study participation, thereby fulfilling the World Health Organization (WHO) guideline on PA for youth. Approximately a quarter of participants (24%) were not members of a sports club, while half were members of one sports club and about a quarter (26%) were members of more than one sports club. On average, participants reported medium to high daily well-being (M = 4.29, SD = 0.89). The descriptive statistics of the constructs employed in the models are provided in Table 1. The intraclass correlation coefficient (ICC) indicates the proportion of total variance that reflects the between-person variance; thus, how strongly values from one individual resemble each other. In our sample, 62% of the variance in well-being could be explained by between-person differences, so 38% of the variance consisted of within-person fluctuations and measurement error. We observed a significant but small correlation between screen time and digital social contacts on the between-person level (r = .257, p < .001) and very small on the within-person level (r = .039, p < .001).

Hypothesis Testing

The results of the multilevel model testing all directional hypotheses (1, 2, 3) are provided in Table 2.

Regarding total PA, we found a significant positive relation to adolescent well-being between (γ_{01} = 0.03, 95% CI[0.01, 0.04], p = .005) and within individuals (γ_{10} = 0.01, 95% CI[0.00, 0.01], p < .001). This suggests that across assessments, adolescents with higher levels of total PA reported better well-being. Furthermore, adolescents reported higher well-being on days with more PA than usual. The random effect of total PA was significant, indicating substantial differences in its within-person relation to well-being ($SD(\upsilon_{1i})$ = 0.01).

Regarding overall social contacts, we found no significant between-person effect (γ_{02} = 0.05, 95% CI[−0.06, 0.16], p = .396). Individuals with overall more social contacts did not generally report higher well-being. However, we found a significant positive within-person association (γ_{20} = 0.01, 95% CI[0.01, 0.02], p < .001). Hence, on days with more social contacts than usual, adolescents reported better well-being. The random effect of social contacts was significant, indicating substantial differences in its within-person relation to well-being ($SD(\upsilon_{2i})$ = 0.02). Furthermore, the random effects of intercept and social contacts were negatively correlated ($r(\upsilon_{oi}, \upsilon_{3i})$ = −0.51), indicating that participants with higher initial well-being showed a smaller association between number of social contacts and well-being.

Regarding screen time, we found significant negative effects between (γ_{30} = −0.21, 95% CI[−0.28, −0.13], p < .001) and within individuals (γ_{03} = −0.04, 95% CI [−0.07, −0.02], p = .001). These findings suggest that adolescents with overall higher screen time reported lower well-being across observations. Adolescents also reported better well-being on days with less screen time than usual. The random effect of screen time was significant, indicating substantial differences in its within-person relation to well-being ($SD(\upsilon_{3i})$ = 0.09).

Concerning the control variables, we found a significant positive relation of well-being and study day (γ_{40} = 0.01,

Table 2. Multilevel model to test the between- and within-person association between adolescents' well-being and their daily behaviors (total PA, social contacts, screen time)

Fixed effects		Estimates	CI	*p*
Intercept	γ_{00}	4.30***	4.11–4.49	<.001
Total PA (between-person)	γ_{01}	0.03**	0.01–0.04	.005
Total PA (within-person)	γ_{10}	0.01***	0.00–0.01	<.001
Social contacts (between-person)	γ_{02}	0.05	−0.06 to 0.16	.396
Social contacts (within-person)	γ_{20}	0.01***	0.01–0.02	<.001
Screen time (between-person)	γ_{03}	−0.21***	−0.28 to −0.13	<.001
Screen time (within-person)	γ_{30}	−0.04**	−0.07 to −0.02	.001
Sex (female)	γ_{04}	−0.15	−0.39 to 0.08	.203
Age	γ_{05}	−0.02	−0.09 to 0.05	.584
Study day	γ_{40}	0.01***	0.01–0.01	<.001
School day (yes)	γ_{50}	−0.09***	−0.14 to −0.04	<.001
Quarantine (yes)	γ_{60}	0.12	−0.53 to 0.76	.722
Random effects			**Estimates**	***p*[a]**
Level 2 (between-person)				
Intercept		$SD(\upsilon_{oi})$	0.61***	<.001
Total PA		$SD(\upsilon_{1i})$	0.01**	.004
Social contacts		$SD(\upsilon_{2i})$	0.02**	.005
Screen time		$SD(\upsilon_{3i})$	0.09***	< .001
Intercept and total PA		$r(\upsilon_{oi}, \upsilon_{1i})$	−0.20	.232
Intercept and social contacts		$r(\upsilon_{oi}, \upsilon_{3i})$	−0.51*	.013
Intercept and screen time		$r(\upsilon_{oi}, \upsilon_{3i})$	0.09	.339
Total PA and social contacts		$r(\upsilon_{1i}, \upsilon_{3i})$	0.49	.591
Total PA and screen time		$r(\upsilon_{1i}, \upsilon_{3i})$	0.51	.352
Social contacts and screen time		$r(\upsilon_{3i}, \upsilon_{3i})$	0.30	.672
Level 1 (within-person)				
Residual		$SD(\varepsilon_{ti})$	0.52	
Autocorrelation		φ	0.23***	<.001

Note. N = 125 adolescents, n = 2,464 observations, *p < .05. **p < .01. ***p < .001. [a] p-values for the random effects were obtained by conducting pairwise likelihood-ratio tests comparing two models including the same parameters except for the random effect of interest.

95% CI [0.01, 0.01], p < .001) and a significant negative relation with school day (γ_{50} = −0.09, 95% CI [−0.14, −0.04], p < .001). The increase of well-being over study course is congruent with findings from other ambulatory assessment studies suggesting that repeatedly reflecting on one's well-being can increase it (De Vries et al., 2021). Furthermore, the random intercept was significant ($SD(\upsilon_{oi})$ = 0.61), indicating substantial differences in individual well-being at study start.

Explorative Analyses

Here, we will only describe the findings relevant to our explorative hypotheses. The models testing the explorative hypotheses (A, B, C) and the results are provided in ESM 2.

In explorative analysis A examining possible inter-relations between daily behaviors, we found no such inter-relations as no two-way interaction was significant (all p > .05).

In explorative analysis B, we examined PA and SA in different contexts (sports club, leisure time, school). Within individuals, we observed positive main effects for PA (γ_{40} = 0.013, 95% CI[0.008, 0.017], p < .001), SA in leisure time (γ_{20} = 0.011, 95% CI[0.006, 0.016], p < .001), and SA in sports club (γ_{10} = 0.006, 95% CI[0.000, 0.011], p = .048), and the interaction between PA and SA in leisure time was slightly negative (γ_{80} = −0.001, 95% CI [−0.002, −0.000], p < .001). Between individuals, PA was positively related to well-being (γ_{04} = 0.034, 95% CI [0.001, 0.067], p = .044).

In explorative analysis C, we examined in-person and digital social contacts. We found a significant positive effect of in-person social contacts within (γ_{20} = 0.02, 95% CI[0.02, 0.03], p < .001), but not between individuals (γ_{02} = −0.02, 95% CI[−0.15, 0.12], p = .804). For digital social contacts, we found no significant relation to well-being (between: γ_{01} = 0.05, 95% CI[−0.08, 0.19], p = .422; within: γ_{10} = 0.01, 95% CI[−0.01, 0.02], p = .456). Only the random effect of digital social contacts ($SD(\upsilon_{1i})$ = 0.04) was significant.

Discussion

In a 28-day ambulatory assessment study, we examined associations between adolescents' daily PA, SA, social contacts, screen time, and their well-being one year after the COVID-19 pandemic onset. Consistent with Hypothesis 1, total PA was positively related to well-being between and within individuals. The between-person relation is consistent with previous findings (Marckhoff et al., 2022) and strengthens the understanding that being overall more physically active is related to better well-being in youth. This is important to highlight as only a minority of our sample fulfilled the WHO PA guideline. Additionally, higher levels of daily total PA may aid adolescent well-being: On days with more total PA than usual, participants reported better well-being.

Explorative analysis B investigating PA and SA in different contexts revealed that PA, SA in sports clubs, and SA in leisure time were positively related to well-being within individuals and PA also between individuals. This emphasizes the importance to facilitate participation in SA in

sports clubs and leisure time during the pandemic. SA in school, however, was not related to well-being. This might be explained by this type of SA not being voluntary and, thus, related to a higher variability in motivation (Bagøien et al., 2010).

Hypothesis 2 was supported by our data within individuals: Adolescents reported better well-being on days with more social contacts than usual. However, between individuals, Hypothesis 2 was not supported. Substantial differences in the within-person association suggest that the role of social contacts for well-being might be influenced on the between-person level by, for instance, personality traits (e.g., self-esteem; Çivitci & Çivitci, 2009). We could not consider personality traits in our analysis, which might explain the null finding.

Our explorative Hypothesis C was supported: In-person social contacts were positively related to well-being within individuals, while the within-person relation to digital social contacts was not significant and differed substantially between individuals. This supports previous findings (Jusienė et al., 2022) and emphasizes the relevance of in-person social contacts for adolescent well-being.

Hypothesis 3 assuming a negative relation of screen time and well-being was confirmed: Consistent with another ambulatory assessment study conducted during the pandemic (Camerini et al., 2022), adolescents with overall higher screen time reported lower well-being. We also observed a negative within-person relation, albeit it was smaller in magnitude. Adolescents reported lower well-being on days with more screen time than usual, contradicting the other study's null finding within individuals. This inconsistency might be explained methodologically: Camerini and colleagues analyzed monthly data, while we collected daily data.

As we tested all daily behaviors in one model, our findings allow us to conclude that the effects of the single daily behaviors held true when controlling for the others. Our explorative analysis A revealed that the daily behaviors were not inter-related, suggesting that the relations between the single daily behaviors and well-being do not depend on the levels of the other daily behaviors.

Practical Implications

In the pandemic context, the following practical conclusions can be drawn from our study when discussing restrictions to daily life: Opportunities for PA should be facilitated and encouraged to aid adolescent well-being. Since negative pandemic-related mental health outcomes can be expected, the treatment of mental health problems will pose a long-lasting challenge (Fegert et al., 2020). PA and SA are cost-efficient as well as easily and widely applicable and should be considered in health promotion.

While previous work suggests that school-based fitness interventions could aid adolescent well-being (Cataldi et al., 2021), our findings indicate that school might not be the best context for SA to benefit well-being. Instead, our study highlights the importance of enabling SA in sports clubs or in leisure time (e.g., by conducting COVID-19 rapid tests before practice). We also found PA including walking or active transport (e.g., biking) to be beneficial, and thus, active commuting to school should be promoted.

Furthermore, our study highlights the relevance of in-person social contacts compared to digital ones. Albeit social isolation is important to control the spread of infectious diseases, its negative impact on adolescent well-being should be considered (Thiel et al., 2021). Opportunities for social interactions under safety standards (e.g., wearing face masks) should be enabled.

The observed negative relation of screen time and well-being between and within individuals in our study highlights the importance of dependable daily routines to mitigate aversive pandemic-related effects on adolescent well-being (Racine et al., 2021). Our findings suggest that limited *and* stable screen times are one possibility of reducing adverse effects.

Limitations and Suggestions for Future Research

Despite the numerous strengths of our study examining the relation of daily behaviors and well-being in adolescents, some limitations should be considered: Low socioeconomic status (SES) has been reported as a risk factor for negative pandemic-related effects on well-being (Vogel et al., 2021), but in our study, we could not control for SES. Our sample size was limited, and the sample was not representative for the general population, with many participants attending higher-level education of the German educational system.

Regarding our measures, we observed a significant correlation between screen time and digital social contacts; however, it was only small (between-person) or very small (within-person) in magnitude. Still, this suggests that these constructs cannot be completely separated. In our study, we examined quantity of social contacts because this was strongly affected by pandemic-related restrictions. Future research could examine quality of social contacts and its relation to well-being. Furthermore, all variables were assessed through self-report. More objective measures may be better to assess rather objective data (e.g., accelerometer-based PA-assessment, digital applications for screen time measurement), but participant

burden should be considered. It should also be mentioned that we exclusively examined linear relations between the variables and, thus, cannot exclude the possibility of nonlinear associations.

Our results indicate that future research should further investigate possible negative influences of daily behaviors during the pandemic. The observed random effects for all examined daily behaviors imply that possible between-person moderators affecting the within-person relationships should also be investigated (Sudeck et al., 2018). Methodological implications can be drawn from associations observed on the within-person level, but not on the between-person level (i.e., SA in sports club, SA in leisure time, social contacts). To examine the role of these behaviors, comparisons between individuals as conducted in cross-sectional studies are insufficient. Thus, future research in this field should employ more ambulatory assessment studies accounting for differences between and within individuals.

Electronic Supplementary Material

The electronic supplementary material is available with the online version of the article at https://doi.org/10.1027/2151-2604/a000518

ESM 1. Tables E3–E4: The tables show the questionnaires employed in the study (baseline, daily, follow-up).

ESM 2. Explorative analyses. The file contains all detailed information about the explorative analyses and their results.

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History
Received August 11, 2022
Revision received January 9, 2023
Accepted January 23, 2023
Published online May 30, 2023

Acknowledgments
The authors wish to thank all adolescents for participating in this study. Additionally, we want to thank Sven Waigel, Alexander Wütz, and Stephan Gutermann for their help and advice in participant recruitment and study planning, as well as Tobias Renner and Ute

Dürrwächter for their expert advice on the study design. Furthermore, we thank our student assistants for their help with data collection and preparation.

Publication Ethics
Informed consent was obtained from all participants included in the study and from each one parent. The study procedure was approved by the ethics committee of the University of Tübingen and the regional board of Tübingen.

Authorship
Anne Eppinger Ruiz de Zarate, data curation, formal analysis, investigation, methodology, project administration, visualization, writing – original draft, writing – review & editing; Ansgar Thiel, conceptualization, funding acquisition, methodology, resources, supervision, writing – review & editing; Gorden Sudeck, conceptualization, formal analysis, funding acquisition, methodology, resources, supervision, writing – review & editing; Katja Dierkes, data curation, investigation, project administration, writing – review & editing; Jannika M. John, writing – review & editing; Andreas M. Nieß, conceptualization, methodology; Caterina Gawrilow conceptualization, funding acquisition, methodology, resources, supervision, writing – review & editing. All authors approved the final version of the article.

Open Data
Open Materials: The information needed to reproduce all of the reported methodology is available in the electronic supplementary material. The data that support the findings of this study are available upon request from the corresponding author, Anne Eppinger Ruiz de Zarate. The data are not publicly available due to privacy restrictions.

Funding
This research was supported by the Ministry of Social Affairs, Health, and Integration of the German federal state of Baden-Württemberg to Ansgar Thiel. Open access publication enabled by the University of Tübingen, Germany.

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