Variability and Stability of Physical Activity in Children and Adolescents – Activity Compensation from a Public Health Perspective

Variabilität und Stabilität körperlicher Aktivität bei Kindern und Jugendlichen – Aktivitätskompensation aus Public Health Perspektive

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List of Publications Arising from Dissertation

Manuscript A:

Beck, F., Siefken, K., & Reimers, A. K. (2022). Physical activity in the face of the Covid-19 pandemic: changes in physical activity prevalence in Germany. *Deutsche Zeitschrift für Sportmedizin/German Journal of Sports Medicine*, *73*(5), 175-183. https://doi.org/10.5960/dzsm.2022.537

Manuscript B:

Beck, F., Marzi, I., Eisenreich, A., Seemüller, S., Tristram, C., & Reimers, A. K. (2023). Determination of cut-off points for the Move4 accelerometer in children aged 8–13 years. *BMC Sports Science, Medicine and Rehabilitation, 15*(1). https://doi.org/10.1186/s13102-023-00775-4

Manuscript C:

Beck, F., Engel, F. A., & Reimers, A. K. (2022). Compensation or Displacement of Physical Activity in Children and Adolescents: A Systematic Review of Empirical Studies. *Children*, *9*(3). https://doi.org/10.3390/children9030351

Manuscript D:

Beck, F., Dettweiler, U., Sturm, D. J., Demetriou, Y., & Reimers, A. K. (2022). Compensation of overall physical activity in (pre)adolescent girls – the CReActivity project. *Archives of Public Health, 80*(1), 244. https://doi.org/10.1186/s13690-022-01002-1

Manuscript E:

Beck, F., Swelam, B. A., Dettweiler, U., Krieger, C., & Reimers, A. K. (2024). Compensatory behavior of physical activity in adolescents – a qualitative analysis of the underlying mechanisms and influencing factors. *BMC Public Health, 24*(1), 158. https://doi.org/10.1186/s12889-023-17519-1

Manuscript F:

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List of Abbreviations

ComPAS	**Com**pensatory behavior of **p**hysical **a**ctivity in adolescent**s**
CReActivity	**Cre**ating higher physical **activity** levels
EMPADIC	**E**xamination of **m**ethods for recording **p**hysical **a**ctivity and its **d**eterminants **i**n **c**hildren aged 8 to 13 years
LPA	light physical activity
MET	metabolic equivalent
MoMo	Motorik-Modul
MPA	moderate physical activity
MVPA	moderate to vigorous physical activity
NCD	non-communicable disease
PA	physical activity
PE	physical education
SB	sedentary behavior
SES	socioeconomic status
VPA	vigorous physical activity

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1 Summary

1.1 Summary in English

Variability and Stability of Physical Activity in Children and Adolescents – Activity Compensation from a Public Health Perspective

Regular physical activity (PA) is associated with various short- and long-term health benefits in children and adolescents and can prevent suffering from non-communicable diseases in adulthood (Janssen & LeBlanc, 2010; Poitras et al., 2016; Warburton & Bredin, 2017). To address these benefits, PA guidelines exist worldwide (Rütten & Pfeifer, 2016; World Health Organization, 2010). Despite these recommendations and the known health benefits, inactivity of children and adolescents remains a global issue (Guthold et al., 2020). Though numerous interventions have aimed to modulate children's PA to the recommended levels, PA promotion programs have had mixed success and changes are typically not sustained (Dobbins et al., 2013; Messing et al., 2019). To develop interventions and to efficiently promote PA levels, there is a need to have a deeper look on (habitual) PA behavior in terms of stability and variability of PA as this may help to understand and promote activity behavior of children and adolescents in a holistic way.

In general, PA levels in children and adolescents underly variability that occurs in everybody's daily life (affected by for example weather, season, age…), as it is unlikely on a within subject level, that one would engage in the same amount of PA each day. Overall, it is determined that the intra-individual variability of children's and youths' PA level deviates from their mean PA level with ±20-25% (Eisenmann & Wickel, 2009; Levin et al., 1999). Further impacts based on various factors associated with health behavior (socioecological model (McLeroy et al., 1988)) can cause greater changes in PA behavior than the regular intra-individual variability of ±20-25%. In **Manuscript A** we illustrate how this variability is or is not affected by policy restrictions during the Covid-19 pandemic and therefore, we conducted a rapid review aiming to get on overview of changes in PA levels during lockdown. However, in the context of PA, the issue of stability of PA is particularly relevant from a public health perspective as epidemiological studies highlight that continuous and stable activity behavior reduces the risk of several diseases (Hernelahti et al., 2004; Twisk et al., 2000). According to Rowland (1998), there exists a biological control mechanism (ActivityStat hypothesis), that leads to stable PA levels, i.e. activity compensation. Activity compensation suggests, that an increase of PA at one time point may result in a subsequent decrease of PA at another time point (and vice versa), in order to maintain energy stability over time (Gomersall et al., 2013; Rowland, 1998). However, activity compensation is poorly understood. As such, this thesis wants to explore activity compensation in children and adolescents from a public health perspective using different measurement approaches.

To measure variability and stability, respectively compensatory behavior, different measurement methods are available. Firstly, to gain information about the compensatory mechanism, device-based approaches can be used as these produce quantifiable and accurate values (Reilly et al., 2008). One

example for device-based methods is accelerometry. These devices need to be validated and calibrated for each age group as body structures and thus, locomotion is not equal in children and adults (Ridgers & Fairclough, 2011; Strath et al., 2013) (**Manuscript B**). Having then appropriate measurement methods on hand, compensatory behavior can be assessed. Overall, there is an ongoing debate concerning whether activity compensation occurs (Reilly, 2011; Wilkin, 2011) and further, little is known about how compensation may occur, to whom it may occur, and any reasons for its occurrence. Thus, before conducting empirical studies concerning activity compensation, there is a need to get knowledge about the state of research. Therefore, we performed a systematic review to get an overview of compensatory behavior in children and adolescents aged 0-19 years (**Manuscript C**). By including only studies with a device-based approach, compensatory mechanisms were analyzed across different categories, which seemed to be helpful for understanding compensation. Within the 77 included studies, the ActivityStat hypothesis could be neither confirmed nor rejected with a prevalence of compensation in 50% of the included studies and a tendency of compensation within interventional studies. Further, the results highlighted that little research had explored influencing factors of compensatory responses. Finally, there was a lack of consistency in methodology used to assess compensation (e.g., between-person or group analyses, varying timespans of potential compensatory responses, study designs, etc.), making it difficult to draw firm conclusions surrounding the existence of an ActivityStat. To address these limitations, we performed a secondary data analysis of the CRreActivity study data (**Manuscript D**) and focused on the timespan of compensation as well as sociodemographic data (age, weight status and socioeconomic status (SES)) as potential moderators for compensatory behavior in (pre)adolescent girls. The data indicated compensatory behavior within-day (morning-afternoon) as well as between-day (weekdays-weekend days) in about 60% of all observation points. Further multilevel analysis indicated that sociodemographic data did not moderate activity compensation and this behavior is rather a quite individual behavior.

Summarizing the findings from the previous compensation articles, inconclusive results concerning activity compensation in children and adolescents could be identified. Even if device-based activity monitoring is essential in providing quantitative data and assessing compensatory behavior, it seems not to be sufficient enough to holistically understand activity compensation in children and adolescents. Especially, to provide insights into the behavioral context of activity compensation as well as perception and influencing factors, subjective measurement tools can be helpful to gain a deeper and more holistic understanding of activity compensation. Thus, the following articles focus on subjective measurements and their usefulness in measuring activity behaviors, respectively activity compensation. To focus on individuals and get more information about perception and influencing factors, we conducted a qualitative study (ComPAS study) addressing adolescents aged 11-15 years (**Manuscript E)**. By comparing an activity diary over one week with a habitual weekly schedule (self-reported), we analyzed deviations in PA levels and potential subsequent compensatory responses. Our analyses indicated inconclusive results concerning occurrence and timespan of compensatory responses. Furthermore, few adolescents perceived that they compensated. However, the interviews identified potential influencing factors for compensatory behavior (e.g., social support, weather, routines…) and thus, may explain the inconclusive results. Especially social support played an important role in activity compensation. This was also confirmed in our last empirical study (MoMo study). Thus, in **Manuscript F,** the aim of this study was to investigate the influence of the family environment, specifically SES, parental support, and having siblings on Covid-19-related changes of PA and screen time behavior in 317 (170 boys, 147 girls) German preschool children using longitudinal data. The results supported the findings of Manuscript E, stating that even if preschool children had a lack of activity due to closure of sports clubs and kindergarten (variability of habitual PA), children receiving parental support seemed to compensate this loss of activity by being active at home (supported by their parents/siblings).

In summary, the findings highlighted that there are various levels that could lead to perturbation and thus changes in one's habitual PA behavior. Following the ActivityStat hypothesis, this variability could be compensated by adapting the PA levels followed by a stable PA level. Our studies investigating compensatory behavior with various measurement methods suggested that whilst compensatory responses may not be consistently predicted, most children and adolescents, regardless of their age, sex/gender or other sociodemographic data, tend to compensate their activity to some degree. Further, the findings of this thesis support a complex interaction between biological control (stating the existence of an ActivityStat) and one's (social and physical) environment (e.g., social support, weather, routines), though further exploration of compensation thresholds and timespans of compensatory responses are needed by using a combination of device-based and subjective measurement methods.

1.2 Summary in German / Zusammenfassung auf Deutsch

Variabilität und Stabilität körperlicher Aktivität bei Kindern und Jugendlichen – Aktivitätskompensation aus Public Health Perspektive

Regelmäßige körperliche Aktivität (kA) ist mit verschiedenen kurz- und langfristigen gesundheitlichen Vorteilen für Kinder und Jugendliche verbunden und kann dazu beitragen, chronische, nicht übertragbare Krankheiten im Erwachsenenalter zu verhindern (Janssen & LeBlanc, 2010; Poitras et al., 2016; Warburton & Bredin, 2017). Um von diesen Vorteilen zu profitieren, existieren weltweit Aktivitätsrichtlinien (Rütten & Pfeifer, 2016; World Health Organization, 2010). Trotz dieser Empfehlungen und der bekannten gesundheitlichen Vorteile bleibt die Inaktivität von Kindern und Jugendlichen ein globales Problem (Guthold et al., 2020). Obwohl zahlreiche Interventionen darauf abzielten, die Aktivität von Kindern auf die empfohlenen Levels zu modulieren, waren Aktivitätsförderungsprogramme nur teilweise erfolgreich, und Veränderungen werden in der Regel nicht aufrechterhalten (Dobbins et al., 2013; Messing et al., 2019). Um Interventionen zu entwickeln und kA Levels effizient zu fördern, ist es erforderlich, einen tieferen Blick auf (gewohnheitsmäßiges) kA-Verhalten im Hinblick auf Stabilität und Variabilität zu werfen, da dies dazu beitragen kann, das Aktivitätsverhalten von Kindern und Jugendlichen ganzheitlich zu verstehen und zu fördern.

Generell unterliegt die kA von Kindern und Jugendlichen einer Variabilität, die im täglichen Leben jedes Einzelnen auftritt (beeinflusst durch z.B. Wetter, Jahreszeit, Alter usw.), da es unwahrscheinlich ist, dass jemand auf individueller Ebene jeden Tag die gleiche Menge an Aktivität aufweist. Insgesamt wird festgestellt, dass die intra-individuelle Variabilität des kA-Niveaus von Kindern und Jugendlichen mit ±20-25 % von ihrem mittleren kA-Niveau abweicht (Eisenmann & Wickel, 2009; Levin et al., 1999). Weitere Einflüsse basierend auf verschiedenen Faktoren im Zusammenhang mit Gesundheitsverhalten (sozioökologisches Modell (McLeroy et al., 1988)) können größere Veränderungen im Aktivitätsverhalten verursachen als die reguläre intraindividuelle Variabilität von ±20-25%. In **Manuskript A** veranschaulichen wir, wie die Variabilität der kA nach politischen Einschränkungen, die das gewohnheitsmäßige Verhalten beeinflussen, aussehen könnte. Wir führten hierzu ein Rapid Review durch, um einen Überblick über Veränderungen im Aktivitätsverhalten während der Covid-19-Pandemie zu erhalten.

Im Zusammenhang mit kA ist jedoch die Frage der Stabilität von kA aus Public-Health-Perspektive besonders relevant, da epidemiologische Studien darauf hinweisen, dass kontinuierliches und stabiles Aktivitätsverhalten das Risiko für verschiedene Krankheiten reduziert (Hernelahti et al., 2004; Twisk et al., 2000). Laut Rowland (1998) gibt es einen biologischen Steuermechanismus (ActivityStat Hypothese), der zu stabilen Aktivitätsniveaus führt, d.h. Aktivitätskompensation. Aktivitätskompensation deutet darauf hin, dass eine Zunahme der kA zu einem bestimmten Zeitpunkt zu einer nachfolgenden Abnahme der kA zu einem anderen Zeitpunkt führen kann (und umgekehrt), um die Energiestabilität im Laufe der Zeit aufrechtzuerhalten (Gomersall et al., 2013; Rowland, 1998). Die

Aktivitätskompensation ist jedoch unzureichend untersucht und verstanden. Diese Arbeit versucht daher, die Aktivitätskompensation bei Kindern und Jugendlichen aus Public-Health-Perspektive unter Verwendung unterschiedlicher Messmethoden zu erforschen.

Zur Messung von Variabilität und Stabilität bzw. Kompensationsverhalten stehen verschiedene Messmethoden zur Verfügung. Zunächst können gerätebasierte Ansätze verwendet werden, um Informationen über den Kompensationsmechanismus zu erhalten, da diese quantifizierbare und genaue Werte liefern (Reilly et al., 2008). Ein Beispiel für gerätebasierte Methoden sind Beschleunigungssensoren. Diese Geräte müssen für jede Altersgruppe kalibriert werden muss, da sich Körpereigenschaften und somit die Fortbewegung bei Kindern und Erwachsenen unterscheiden (Ridgers & Fairclough, 2011; Strath et al., 2013) (**Manuskript B**). Sobald geeignete Messmethoden zur Verfügung stehen, kann das kompensatorische Verhalten bewertet werden. Generell gibt es eine anhaltende Debatte darüber, ob Aktivitätskompensation stattfindet (Reilly, 2011; Wilkin, 2011), und darüber hinaus ist wenig darüber bekannt, wie Kompensation auftreten kann, bei wem sie auftreten kann und aus welchen Gründen sie auftritt. Bevor empirische Studien zur Aktivitätskompensation durchgeführt werden, ist es erforderlich, einen Überblick über den Forschungsstand zu erhalten. Daher haben wir als ersten Schritt eine systematische Übersichtsarbeit geschrieben, um einen Überblick über das Kompensationsverhalten bei Kindern und Jugendlichen zu erhalten (**Manuskript C**). Es wurden nur Studien mit gerätebasiertem Ansatz eingeschlossen und Kompensationsmechanismen in verschiedenen Kategorien analysiert, was für das Verständnis der Kompensation hilfreich zu sein schien. Anhand der 77 eingeschlossenen Studien konnte die ActivityStat Hypothese weder bestätigt noch abgelehnt werden, wobei in 50% der eingeschlossenen Studien eine Tendenz zur Kompensation in interventionsbasierten Studien festgestellt wurde. Die Ergebnisse zeigten jedoch, dass wenig Forschung die beeinflussenden Faktoren kompensatorischer Reaktionen untersucht hatte. Schließlich mangelte es an Konsistenz in der angewandten Methodik zur Bewertung von Kompensation (z. B. zwischen Personen oder Gruppenanalysen, unterschiedliche Zeiträume, Studiendesigns usw.), was es schwierig macht, konsistente Schlussfolgerungen zur Existenz eines ActivityStat zu ziehen. Um diese Einschränkungen zu adressieren, führten wir eine Sekundärdatenanalyse der CReActivity Daten durch (**Manuskript D**) und konzentrierten uns auf den Zeitraum der Kompensation sowie auf soziodemografische Daten (Alter, Gewichtsstatus und sozioökonomischer Status) als potenzielle Moderatoren für kompensatorisches Verhalten bei präadoleszenten Mädchen. Die Daten zeigten kompensatorisches Verhalten innerhalb des Tages (Morgen-Nachmittag) sowie zwischen den Tagen (Wochentage-Wochenendtage) bei etwa 60% aller Beobachtungspunkte. Mehrebenen-Analysen deuteten darauf hin, dass soziodemografische Daten keine Aktivitätskompensation moderierten und dieses Verhalten eher ein individuelles Verhalten ist. Zusammenfassend konnten aus den vorherigen Artikeln zur Kompensation uneindeutige Ergebnisse bezüglich der Aktivitätskompensation bei Kindern und Jugendlichen identifiziert werden. Selbst wenn die gerätebasierte Aktivitätserfassung hilfreich ist, um quantitative Daten zu generieren und kompensatorisches Verhalten zu bewerten, scheint sie nicht ausreichend genug zu sein, um die Aktivitätskompensation bei Kindern und Jugendlichen ganzheitlich zu verstehen. Insbesondere zur Erklärung des Verhaltenskontexts der Aktivitätskompensation sowie der Wahrnehmung und Einflussfaktoren können subjektive Messinstrumente hilfreich sein. Daher haben sich die folgenden Artikel auf subjektive Messungen und deren Nützlichkeit zur Erfassung von Aktivitätsverhalten bzw. Aktivitätskompensation konzentriert.

Um sich auf Einzelpersonen zu konzentrieren und mehr Informationen über Wahrnehmung und Einflussfaktoren zu erhalten, führten wir eine qualitative Studie (ComPAS-Studie) mit Jugendlichen im Alter von 11-15 Jahren durch (**Manuskript E**). Durch den Vergleich eines Aktivitätstagebuchs über eine Woche mit einem gewohnheitsmäßigen Wochenplan (selbstberichtet) analysierten wir Abweichungen und potenzielle anschließende kompensatorische Reaktionen. Unsere Analysen zeigten inkonsistente Ergebnisse hinsichtlich der Häufigkeit und des Zeitrahmens der Kompensation. Darüber hinaus gaben nur wenige Jugendliche an, dass sie kompensierten. Die Interviews identifizierten jedoch potenziell beeinflussende Faktoren für kompensatorisches Verhalten (z. B. soziale Unterstützung, Wetter, Routinen usw.) und können somit die widersprüchlichen Ergebnisse erklären. Insbesondere soziale Unterstützung spielte eine wichtige Rolle bei der Aktivitätskompensation. Dies wurde auch in unserer dritten empirischen Studie (MoMo-Studie) veranschaulicht. Die Studie in **Manuskript F** hatte zum Ziel, den Einfluss des familiären Umfelds, insbesondere des sozioökonomischen Status, der elterlichen Unterstützung und des Vorhandenseins von Geschwistern auf Covid-19-bedingte Veränderungen des körperlichen Aktivitäts- und Bildschirmzeitverhaltens bei 317 (170 Jungen, 147 Mädchen) deutschen Vorschulkindern anhand von Längsschnittdaten zu untersuchen. Die Ergebnisse unterstützten die Ergebnisse von Manuskript E und zeigten, dass selbst, wenn Vorschulkinder aufgrund der Schließung von Sportvereinen und Kindergärten einen Mangel an Aktivität hatten (Variabilität der habituellen kA), Kinder, die elterliche Unterstützung erhielten, diesen Verlust an Aktivität durch Aktivitäten zu Hause zu kompensieren schienen (unterstützt von ihren Eltern/Geschwistern).

Zusammenfassend zeigen die Ergebnisse, dass es verschiedene Faktoren gibt, die zu Störungen des gewohnheitsmäßigen Aktivitätsverhaltens führen können. Nach der ActivityStat-Hypothese könnte diese Variabilität durch Anpassung der Aktivitätsniveaus und anschließendes Erreichen eines stabilen Aktivitätsniveaus kompensiert werden. Unsere Studien zur Erforschung kompensatorischen Verhaltens legten nahe, dass zwar kompensatorische Reaktionen nicht konsistent vorhergesagt werden können, die meisten Kinder und Jugendlichen unabhängig von Alter, Geschlecht oder anderen soziodemografischen Daten aber dazu tendieren, ihre Aktivität in gewissem Maße zu kompensieren. Darüber hinaus belegen die Ergebnisse dieser Arbeit eine komplexe Interaktion zwischen der biologischen Kontrolle (d. h. dem Vorhandensein eines ActivityStats) und dem (sozialen und physischen) Umfeld (z. B. soziale Unterstützung, Wetter, Routinen). Eine weitere Exploration von Kompensationsgrenzen und Zeitrahmen ist jedoch durch die Verwendung einer Kombination von gerätebasierten und subjektiven Messmethoden erforderlich.

2 Physical Activity in Children and Adolescents

2.1 Definition of Physical Activity

Physical activity (PA) is defined as "any bodily movement produced by skeletal muscles that requires energy expenditure" (Caspersen et al., 1985) (pp. 126), whereas sedentary behavior (SB) is defined as "any waking behavior characterized by an energy expenditure ≤1.5 metabolic equivalents (METs), while in a sitting, reclining or lying posture" (Tremblay et al., 2017) (pp. 9). Overall, activity occurs on a continuum from sleep to vigorous active. The common split of intensities for PA is: (a) light-intensity PA (LPA), moderate-intensity PA (MPA), and vigorous-intensity PA (VPA) (Figure 1).

Moreover, while MPA and VPA are usually assessed separately in terms of activity intensity, existing evidence indicates that health outcomes and intervention impacts are generally more advantageous for VPA when analyzing these intensities individually (Costigan et al., 2019; Fairclough et al., 2012; Parfitt et al., 2009). However, in health research, it has been common to combine them as moderate-to-vigorous PA (MVPA) (Poitras et al., 2016), considering the total time spent in both activity intensities.

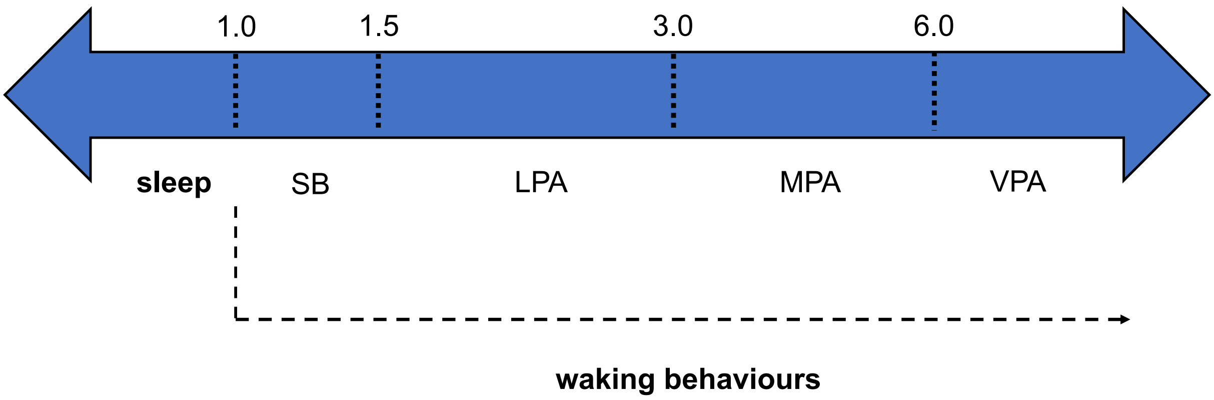

Figure 1: Spectrum of children's activity intensities.
*Note: MET cut-points derived from Pate et al. (1995); Figure adapted from Tremblay et al. (2010).

2.2 Health Benefits of Physical Activity

PA occurs on a continuum from LPA to VPA and there is substantive evidence that regular PA is essential for children's and adolescents' active and healthy lifestyle (Janssen & LeBlanc, 2010; Poitras et al., 2016; Warburton & Bredin, 2017). In more detail, PA serves as a preventative measure against harmful short- and long-term health outcomes (Janssen & LeBlanc, 2010; World Health Organization, 2020b). It also contributes to improving general physical health factors such as weight status, cardiovascular and muscular fitness (Biddle & Asare, 2011; Booth et al., 2012; Janssen & LeBlanc, 2010; Poitras et al., 2016; World Health Organization, 2020b). Furthermore, being regularly physically active reduces the risk of mental health diseases such as anxiety and depression (Biddle & Asare, 2011; Booth et al., 2012; Poitras et al., 2016). In school-aged children and adolescents, PA on a regular basis is also associated with different psychosocial and cognitive health indicators (Biddle & Asare, 2011; Janssen & LeBlanc, 2010; Poitras et al., 2016).

Further, the importance of PA on health gained additional significance since March 2020 as the Covid-19 pandemic impacted everyone's life (Bundesministerium für Gesundheit, 2022). In this context, the importance of engaging in regular PA at appropriate intensity levels has been shown to have a positive impact on the immune system. This includes enhancing immune vigilance and improving immune competence, factors crucial for controlling pathogens (da Silveira et al., 2020; Laddu et al., 2020). Moreover, individuals who consistently engage in high levels of exercise exhibit lower incidence rates of acute respiratory infections, reduced duration and intensity of symptoms, and a decreased risk of mortality from infectious respiratory diseases (Hegde & Solomon, 2015; Laddu et al., 2020; Ozemek et al., 2018; Simpson & Katsanis, 2020).

Regarding the dose-response relationship between volume and intensity of PA for health benefits, Janssen and LeBlanc (2010) stated: the more a child is physically active and the higher the intensity, the greater the health benefits. Contrarily, SB and physical inactivity are listed as two of the main risk factors for non-communicable diseases (NCDs) (Ahmad et al., 2017; Poitras et al., 2016; World Health, 2009). However, the benefit of PA on cardiometabolic risk factors is irrespective of the time spent sedentary (Ekelund et al., 2012).

To benefit from the positive health impact of PA, Germany, as well as many other countries (e.g., Australia, USA, Canada etc.) considered the full activity spectrum when developing national recommendations that suggest how much time children should spend being physically active. These were based on early guidelines suggesting that children and adolescents should be active most days, and engage in at least three sessions of 20-30 minutes of moderate- to vigorous-intensity activity per week (Corbin & Pangrazi, 1998). As more and more research highlighted the benefits of PA on health for children and youth, recommendations were adapted to include 60 minutes of at least MPA per day (Biddle et al., 1998). For many years, the US guidelines (Pate et al., 1995) served also as a guide internationally, until in 2010, the World Health Organization used them as a basis to issue its own recommendations (World Health Organization, 2010), which are nowadays used in many countries as a reference point for national recommendations. The German national recommendations suggest primary-school children as well as adolescents aged 12-18 years being moderately-to-vigorously physically active for 90 minutes or more each day. Sixty minutes of that time can be spent on everyday activities, e.g. at least 12,000 steps/day (Rütten & Pfeifer, 2016). Further, in 2020, the World Health Organization published revised guidelines on PA and SB including recommendations for different age groups and groups with special needs (e.g., people living with disabilities) (World Health Organization, 2020b). For children and adolescents between 5 and 17 years, the World Health Organization (2020b) recommends: (1) moderate- to vigorous-intensity, mostly aerobic PA, at least an average of 60 minutes daily; (2) vigorous-intensity aerobic activities, as well as those that strengthen muscle and bone, at least three days a week; (3) a limited amount of time spent being sedentary (especially recreational screen time). An overview of differences between the national German guideline and the World Health Organization guideline from 2010 and 2020 can be seen in Table 1.

Table 1. Selected PA recommendations for children and adolescents in comparison.

Age	National Recommendations of Germany (Rütten & Pfeifer, 2016)	World Health Organization Guidelines 2010 (World Health Organization, 2010)	World Health Organization Guidelines 2019/2020 (World Health Organization, 2020b)
1	Infants and toddlers should move as much as possible and be hindered as little as possible in their natural urge to move; care should be taken to ensure safe environmental conditions		Infants should be physically active several times a day in various ways, especially through interactive play on the floor; the more the better. For those who are not yet mobile, this includes at least 30 min in the prone position throughout the day while awake.
2			Infants 1-2 years of age should achieve at least 180 min/day with/in a variety of physical activities of any intensity, including moderate to vigorous physical activity, throughout the day; the more, the better
3			Young children 3-4 years of age should achieve at least 180 min/day with/in a variety of physical activities of any intensity that includes at least 60 min of moderate-to-vigorous physical activity spread throughout the day; the more, the better
4	For kindergarten children, the goal is to achieve a total physical activity time of 180 minutes/day or more, which may consist of guided and non-guided physical activity		

5		Children and adolescents aged 5-17 years should have at least 60 minutes of moderate to vigorous physical activity daily. More than 60 minutes of physical activity provides additional health benefits. The majority of daily physical activity should be aerobic. High-intensity activities, including those that strengthen muscles and bones, should also be done at least three days per week.	Children and adolescents should engage in moderate to vigorous physical activity, mostly aerobic, for an average of at least 60 minutes per day throughout the week. Vigorous aerobic activities, as well as those that strengthen muscles and bones, should be done at least 3 days per week
6			
7	Children of elementary school age and older should achieve 90 minutes or more of daily physical activity at moderate to high intensity. 60 minutes of this can be completed through everyday activities, such as at least 12,000 steps		
8			
9			
10			
11			
12	Adolescents should achieve 90 minutes or more of daily physical activity at moderate to high intensity. 60 minutes of this can be completed through everyday activities, such as at least 12,000 steps		
13			
14			
15			
16			
17			
18			

2.3 Physical Activity Levels in Children and Adolescents

The various measurement methods mentioned above can be used to assess PA behavior in children and adolescents. Despite the known health benefits of regular PA, inactivity of children and adolescents is a global issue (Guthold et al., 2020). An international study from 2015 assessed pooled accelerometer data of 27,637 children (aged 5-17 years) from ten countries, and indicated, that only 9.0% of boys and 1.9% of girls met the PA recommendations of at least 60 minutes of MVPA per day (Cooper et al., 2015). Another study assessing pooled self-reported data of 1.6 million adolescents (aged 11-17 years) from 298 school-based surveys across 146 countries and territories revealed that only 19% of adolescents demonstrated sufficient activity levels in 2016 (22.4% among boys; 15.3% among girls) (Guthold et al., 2020). Additionally, a 2020 analysis of self-reported data from 520,533 adolescents' (aged 11-17 years), assessing the frequency of meeting PA guidelines in the last seven days, showed that just 17.2% (22.1% of boys; 12.6% of girls) reported engaging in at least 60 minutes of MVPA every day. Furthermore, 18.1% (14.9% of boys; 21.2% of girls) reported zero days of engagement in at least 60 minutes of MVPA (Marques et al., 2020). The high prevalence of inactivity has also been consistently highlighted by the bi-annual Global Matrix initiative. Launched in 2014, this international scoring system assesses children's (aged 5-17 years) activity across ten core indicators, encompassing overall PA, organized sport, active play, active transportation, SB, physical fitness, family and peers, school, community and environment, and government (Aubert et al., 2019). In 2022, the latest issue reported that 35 of the 57 participating countries/jurisdictions received a failing grade (i.e., D-F grading, interpreted as ≤39% 'success' at meeting recommended guidelines (Aubert et al., 2019)) for 'overall PA levels' category, based on the best available nationally collected data (Aubert et al., 2022). These global PA and SB trends are also true for German children and adolescents (Demetriou et al., 2024). For overall PA, Germany received a D- grade (13-40% of children and adolescents fulfilled the World Health Organization guideline) and only 50% of girls and 43% of boys spend less than two hours a day in their leisure time sitting with digital devices (grade C) (Demetriou et al., 2024). Regarding individual German studies, most recent representative data on World Health Organization PA guideline adherence (≥60 minutes PA per day) among 4- to 17-year-olds are in line with the worldwide prevalence (Schmidt et al., 2020a). Overall, 19.1% of boys and girls are sufficiently physically active. In turn, this means that 78.6% of boys and 83.6% of girls in Germany do not meet the daily recommended amount of PA with an increase in physical inactivity with age (Schmidt et al., 2020a). Interestingly, distinguishing between device-based and subjective measurement methods, Burchartz et al. (2021) stated that 9% of the children and adolescents met the World Health Organization guidelines on each day per week when measured with subjective questionnaire, whereas only 4% with the accelerometer measurement.

In summary, there is a high prevalence of physical inactivity among children and adolescents (Guthold et al., 2020). Nevertheless, a closer look at domain-specific prevalence rates and trends delivers more insights into PA levels and participation. Even if overall PA levels remained relatively stable over the time, representative data on PA in Germany showed an increase in organized PA (sports club and schools) from 2003 to 2017 while non-organized PA (non-organized sports and outdoor play) decreased significantly in all age groups and both girls and boys (Schmidt et al., 2020b). Similar trends are confirmed by international evidence (Booth et al., 2015): While overall PA in children and adolescents remained on a stable level and participation in sports increased, non-organized PA such as active travel decreased significantly over the last decades.

Lastly, focus should lie on sociodemographic differences of PA levels in children and adolescents as this needs to be considered. Whilst national and international data typically focuses on overall child populations, research has highlighted differences in activity prevalence between age groups, sex/gender, time periods, and settings (Aubert et al., 2021; Booth et al., 2015; van Sluijs et al., 2021). Interestingly, at both a national and international level, boys are consistently more active and less sedentary than girls, (Booth et al., 2015; Cooper et al., 2015; Schmidt et al., 2020b; Verloigne et al., 2012) regardless of age. Further, despite these differences, there is a consistently documented decline of PA (Dumith et al., 2011; Nader et al., 2008) paired with an increase in sedentary time as age increases from childhood through adolescence for both sexes (Cooper et al., 2015; Marques et al., 2020) further highlighting the importance of targeting activity in (pre)adolescence.

2.4 Promotion of Children’s and Adolescents’ Physical Activity Levels

As the section above showed, PA levels of children and adolescents are quite low and levels of SB are high (Guthold et al., 2020), there is a need to promote children’s and adolescents’ PA levels. Numerous efforts to promote PA exist across different settings, including schools, family environment or local community settings, and domains (e.g., psychological, social, and environmental), but efficacy in the short and long term has widely varied (Dobbins et al., 2013; Messing et al., 2019; Metcalf et al., 2012). Additionally, the World Health Organization (2018b) stated that global efforts seem to miss the goal and further action is needed

In particular, a 2012 conducted meta-analysis of randomized-controlled trials and controlled clinical trials found minimal intervention effects on overall daily PA in children and adolescents under the age of 16 (Metcalf et al., 2012). In this analysis, across the 28 included studies, PA increased among children in the intervention groups by only four additional minutes per day compared to the control group. The researchers stated that this result had limited clinical significance (Metcalf et al., 2012). Further reviews confirmed this tendency (Altenburg et al., 2016; Jones et al., 2020; McGoey et al., 2015; Oh et al., 2022). Interestingly, Jones et al. (2020) highlighted that in studies that exclusively examined PA during the time in which the intervention took place, there appeared to be a moderate effect on PA. However, in studies that examined PA throughout the school day, or the whole day, the intervention effects were inconclusive or had no evidence of an effect, suggesting that the way that activity was assessed is important (Jones et al., 2020). This phenomenon can be seen in several interventional studies (Aburto et al., 2011; Grasten, 2015; Haapala et al., 2017; Sutherland et al., 2017; Toftager et al., 2014).
Overall, the present findings highlight that there is a lack of sufficient and maintained changes in PA levels. This could be attributed to various reasons like poor and/or inconsistent implementation of interventions, methodological quality in study design, measurement issues, and a lack of external validity of PA and SB interventions (Altenburg et al., 2016; Biddle et al., 2014; McGoey et al., 2015). A further reason may be the biological control of PA behavior that will be explained in more detail in the following chapter (3.2).

Summarizing the previous chapters, PA levels in children and adolescents are insufficient and quite low even if the benefits of PA on health are well documented and activity could take place in different settings/domains. Nevertheless, efforts to promote PA in children and adolescents seem to miss the goal. Thus, to develop interventions and to efficiently promote PA levels, there is a need to have a deeper look on (habitual) PA behavior in terms of stability and variability as this may help to understand and promote PA behavior of children and adolescents in a holistic way.

3 Variability and Stability of (habitual) Physical Activity in Children and Adolescents

The focus of the present thesis lies on the variability and stability of PA behavior within an individual from a public health perspective to gain a deeper understanding of PA behavior in children and adolescents. Variability is the extent to which measured values change in terms of their intensity or form (Rowlands et al., 2015). These changes can be continuous, periodic or irregular. In a more statistical way, variability refers to the property that observed measured values deviate from one another (Pereira et al., 2015; Rowlands et al., 2015). The magnitude of variability is assessed by measures of dispersion. In this context, a clear distinction should be made between dispersion in the sense of variability and its measure (e.g., standard deviation or variance). Furthermore, the intra-individual variability describes the variability of repeated measurements within an individual (Rasch, 1988). In contrast, stability refers to (1) the sturdiness of behavior in the face of internal and external influences, (2) the constancy of behavior across situations and contexts, (3) the invariability of characteristic expressions over time (Wirtz, 2021).

3.1 Variability in the Context of Physical Activity

Variability of PA occurs in everybody's daily life as it is unlikely on an individual level, that one would engage in the exact same amount of activity within a defined time period. To promote PA in an efficient way, it is necessary to know how habitual PA fluctuates over time. The existing studies dealing with the (intra-individual) variability of PA stated that the variability of PA across age groups (PA declines with increasing age (Eisenmann & Wickel, 2009)) or weekdays, as well as seasonal variance are well documented (Atkin et al., 2016; Matthews et al., 2002; Ruedl et al., 2021; Scheers et al., 2012; Wilkin et al., 2006) (see Figure 2).

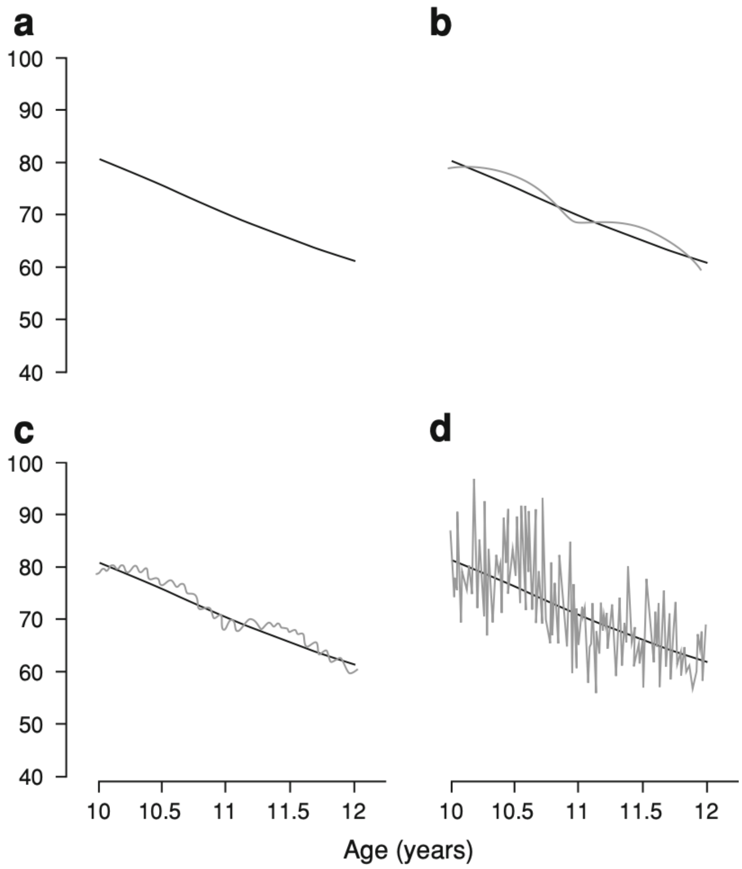

Figure 2: The effects of maturation, seasonal, weekly and random variability on levels of moderate to vigorous physical activity. (a) Shows a declining baseline in moderate to vigorous PA; (b) superimposes the effect of seasonal variation; (c) superimposes on that weekly variation; and (d) adds random intraindividual variability (Gomersall et al., 2013).

Overall, it is determined that the regular intra-individual variability of children's and youths' PA level deviates from their mean PA level with ±20-25% (Eisenmann & Wickel, 2009; Levin et al., 1999), and typical periodicity of activity cycles occur within seven days for those operating on seven-day scheduled weeks (i.e., work or school) (Rowlands et al., 2015) (see Figure 3).

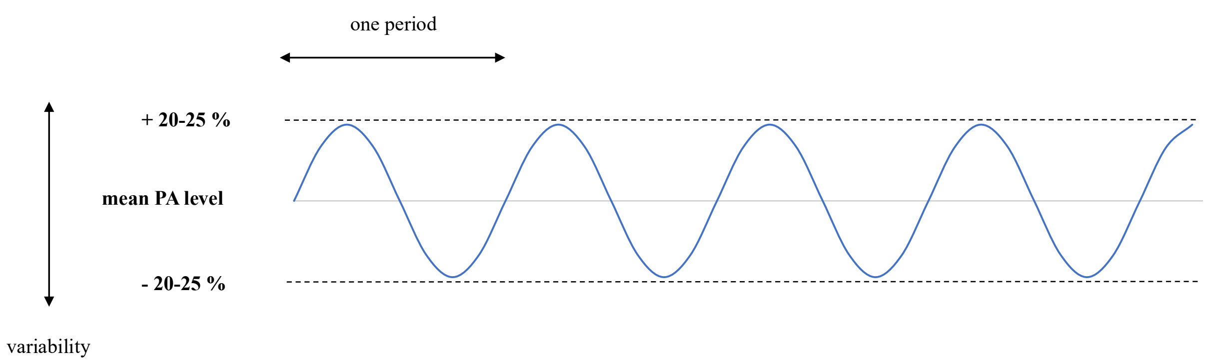

Figure 3: Schematic illustration of intra-individual variability in children and adolescents. Physical activity levels ranging around ±20-25% within one period (e.g., week) (own Figure based on Rowlands et al. (2015)).

3.1.1 *Factors Affecting Variability of Physical Activity Behavior*

Factors that are associated with variability in children and adolescents include season, weekly structure and age (Atkin et al., 2016; Matthews et al., 2002; Ruedl et al., 2021; Scheers et al., 2012; Wilkin et al., 2006) (see Figure 2). However, as seen in the socioecological model (Sallis et al., 2008), there are way more determinants that have an influence on health, and activity behavior, respectively. As one example of health behavior models, the ecological perspective by McLeroy et al. (1988) implies that people's behavior is not only affected by intrapersonal factors (e.g., self-efficacy, attitudes), but also by the social and environmental context in which they live (e.g., social support or policies). Following, multiple levels of contextual influence on health behavior were identified: interpersonal, organizational/institutional, community and public policy level (see Figure 4) (McLeroy et al., 1988). Due to McLeroy et al. (1988), intrapersonal factors include the sociodemographic details/characteristics (e.g., gender, religion, age, ethnicity, socioeconomic status (SES)…) of an individual as well as skills, attitudes or knowledge about health benefits of PA. Furthermore, they stated that interpersonal formal and informal relationships with family members, friends, neighbors, or contacts at school/sport institutions are important sources of influence in the health-related behavior of children and adolescents. On an organizational level, there are institutions that shape behaviors and attitudes due to their institutional characteristics, regulations, rules and cultural expectations. This may include safety, social stigma and health initiatives. Organizational changes are necessary to support long term behavioral adjustments among individuals and are an essential component of creating an institutional culture supportive for health issues, and are a prerequisite for the adoption, implementation, and institutionalization of health promotion programs (Henderson & Baffour, 2015; McLeroy et al., 1988). Especially for children and adolescents' school rules and regulations have an impact on health behavior (Sallis et al., 2008). The next level focuses on community, the environment within defined boundaries an individual lives in that may promote certain norms, provide access to resources, and offer social networks. Built environment, location of community, housing, transportations, community engagement, income level, health and educational facilities are components of communities (McLeroy et al., 1988; Moffatt & Kohler, 2008). Lastly, on a policy level, laws and policies at local, state or federal level may be influential in determining health outcomes. Allocation of funds, policy initiatives that aim to address health behaviors, social equity, and overall infrastructure all are integral in shaping health outcomes (McLeroy et al., 1988).

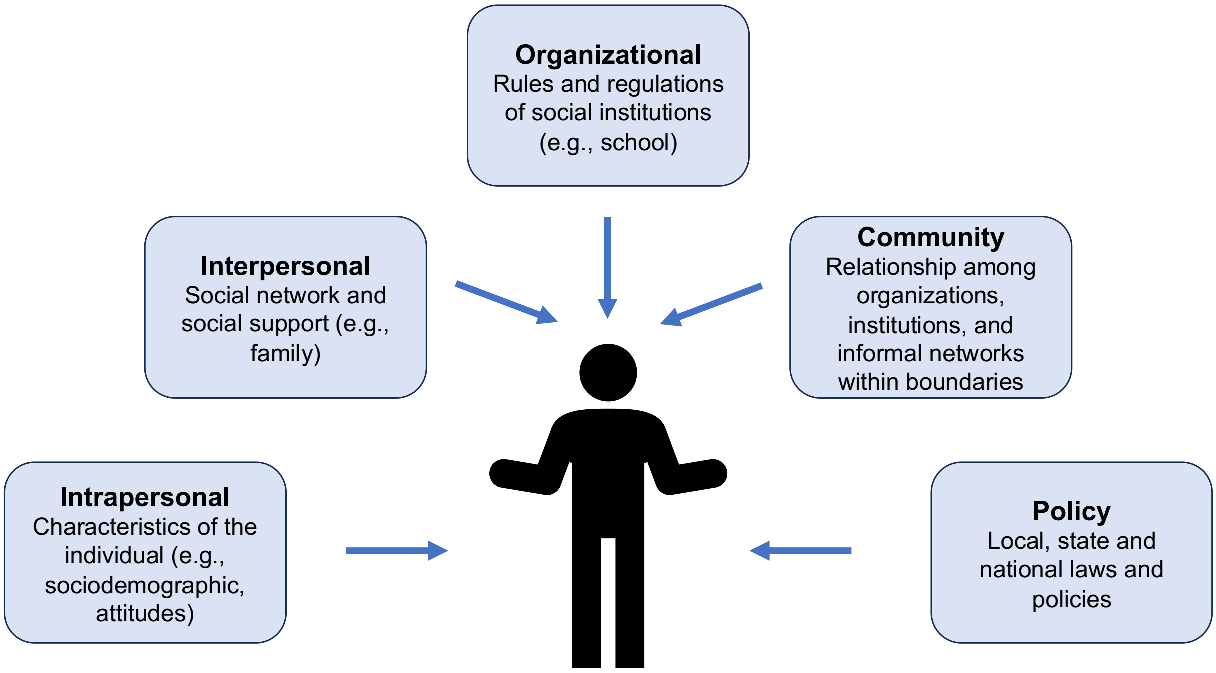

Figure 4: Factors influencing behavior and causing variability in individuals (own illustration based on McLeroy et al. (1988)).

The core concept of ecological models is that one's behavior is influenced by the mentioned five levels (see Figure 4). The ecological model is predominantly used for the development and implementation of interventions (McLeroy et al., 1988; Sallis et al., 2008). Thus, researchers could take the different levels as starting points for interventions or other health promotion programs (Sallis et al., 2008). In more detail, permanent changes on the different levels are implemented to achieve permanent effective health behavior adjustments (e.g., changes in the built environment like more bike lanes will lead to more active travel behavior in general).

Nevertheless, as this concept describes levels that influence one's behavior, this could also be used for explaining factors changing daily activity behavior. More specifically, this model could be used to explain which factors have an impact on one's daily PA behavior that is followed by a change of habitual PA levels.

Accordingly, as the factors won't be stable through the whole lifetime period, changes on the five levels (e.g., in the social or physical environment) will act like a perturbation in one's behavior (McLeroy et al., 1988) and will lead to variability in the (habitual) activity behavior. To explain this in more detail, three points should be highlighted. Generally, it can be focused on long-lasting (e.g., restrictions and measures during Covid-19 pandemic) or only short-term (e.g., school events on one day) changes of determinants of health behavior. In addition, a distinction can be made between changes in PA levels ranging within the individual variability of around ±20-25% (Eisenmann & Wickel, 2009) or outside this threshold. As mentioned earlier, changes within the ±20-25% range are within a typically periodicity (Eisenmann & Wickel, 2009). However, perturbations could lead to deviations greater than this threshold. Furthermore, the direction of change could result either in increases or decreases of PA levels (see Figure 5).

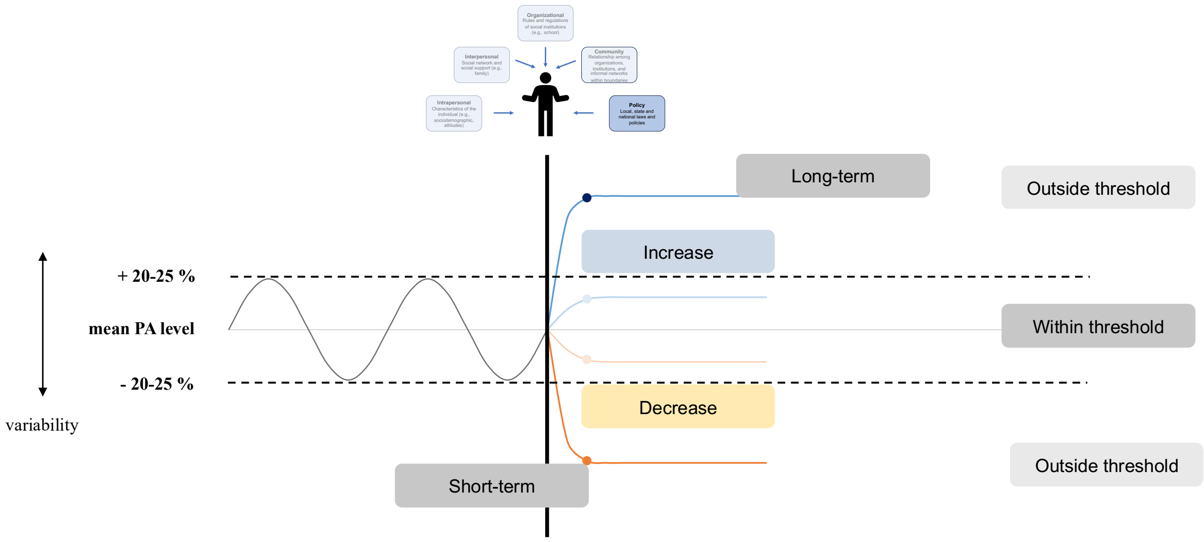

Figure 5: Schematic illustration of habitual activity variability ranging from + 20-25% to – 20-25% (left) and how the subsequent activity level looks like after a perturbation within one's environment (e.g., changes in the policy level) (right).
*Note: ------- represents the threshold for intra-individual variability (Eisenmann & Wickel, 2009). Blue colors show an increase of activity level; Orange colors show a decrease of activity behavior. • represents short-term changes in the habitual activity level following the perturbation, while ——— represents long term changes following the perturbation.

In summary, the determinants on different levels are seen as variables that lead to perturbation of the habitual behavior that is followed by a change in the activity behavior in children and adolescents. For example, as the school organized a sports event (community level), this will act as a perturbation and will have an impact on the habitual behavior. In more detail, the sport event affected the habitual and normal routine inclusive PA level of this day, and this perturbation is followed by a subsequent change of PA as habitual PA behavior is not maintained, respectively by an increase of PA levels in the moment of the sports event compared to habitual PA behavior. Vice versa as training is cancelled due to illness of the coach (interpersonal level), an individuum experiences a perturbation that is followed by a change in his/her habitual behavior (reduction of PA levels).

Another example is the Covid-19 pandemic, that was accompanied by a lot of restrictions concerning the daily (active) living behavior. This is based on changes on the political level, following in a perturbation of habitual behavior that is accompanied by changes in the health behavior, especially the PA behavior.

3.1.2 Manuscript A: Physical Activity in the Face of the Covid-19 Pandemic: Changes in Physical Activity Prevalence in Germany

Beck, F., Siefken, K., & Reimers, A. K. (2022). Physical activity in the face of the Covid-19 pandemic: changes in physical activity prevalence in Germany. *Deutsche Zeitschrift für Sportmedizin/German Journal of Sports Medicine*, *73*(5), 175-183. https://doi.org/10.5960/dzsm.2022.537

Introduction

The outbreak of the Sars-CoV-2 virus, that had a great impact on everybody's life since January 2020, can be seen as an example for a long-lasting perturbation. In March 2020 the outbreak of the virus was characterized as a global pandemic (World Health Organization, 2020a). Consequently, many governments worldwide imposed measures to halt, or at least slow down the spread of the Covid-19 disease. The German government closed schools, sports clubs, other leisure institutions that are relevant to children's and adolescents' organized PA. Furthermore, the government enforced physical distance measures and contact restrictions, allowing no more than two people from different households to meet in public space (Press and Information Office of the Federal Government, 2020b). Practicing organized sports was impeded due to the closing of public sports facilities and sports clubs. However, non-organized sports like going for a walk or playing outside remained allowed if done alone or with people from the same household. This drastic change in public and personal life brought perturbations to the population's lifestyle behavior. On many levels, the world population's daily PA has been impaired for months, affecting the health of a significant portion of the global society. Thus, the objective of our rapid review was to set the scene for PA changes of the German population in face of the Covid-19 pandemic-imposed restrictions and thus, changes in the living circumstances.

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REVIEW

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Physical Activity in the Face of the COVID-19 Pandemic: Changes in Physical Activity Prevalence in Germany

Körperliche Aktivität während der COVID-19-Pandemie: Veränderungen in der Prävalenz körperlicher Aktivität in Deutschland

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Summary

- **Problem:** Physical activity (PA) is a vital component for promoting physical and mental health and for preventing disease. The COVID-19 pandemic has challenged populations from around the world on various levels to maintain and increase overall PA and subsequently led to a shift in physical activity and its health outcomes. This paper synthesizes the current literature on PA during the COVID-19 pandemic in the German population.
- **Methods:** In a rapid review we identified 31 studies that examined PA behavior in children, adolescents, young adults and adults from Germany during the COVID-19 pandemic.
- **Results:** Findings indicate predominantly a decline in PA among all age groups. PA levels in children and adolescents increased in a few studies predominantly during the first lockdown. Types of sports and intensities changed within the German population during the pandemic. Quality assessment of the included studies revealed a lack of adequately reported PA measures as well as a lack of sufficiently reported study results.
- **Conclusion:** The COVID-19 pandemic led to lower PA levels overall in the German population. Furthermore, the PA inequality has been exacerbated. With the uncertainty of the duration of the pandemic, the continuous and cross-agency efforts of PA promotion across all population groups is key.

Zusammenfassung

- **Problem:** Körperliche Aktivität ist eine wichtige Komponente zur Förderung der körperlichen und geistigen Gesundheit und zur Prävention von Krankheiten. Die COVID-19-Pandemie und die damit einhergehenden Eindämmungsmaßnahmen führten zu entscheidenden Veränderungen im täglichen Leben der Bevölkerung und veränderten damit auch das Bewegungsverhalten. Diese Arbeit fasst die aktuelle Literatur über die Veränderung der körperlichen Aktivität während der COVID-19-Pandemie in der deutschen Bevölkerung zusammen.
- **Methoden:** In einem Rapid Review wurden insgesamt 31 Studien identifiziert, die das körperliche Aktivitätsverhalten von Kindern, Jugendlichen, jungen Erwachsenen und Erwachsenen aus Deutschland während der COVID-19-Pandemie (März 2020-Juli 2021) untersuchten.
- **Ergebnisse:** Die Ergebnisse deuten überwiegend auf einen Rückgang der körperlichen Aktivität in allen Altersgruppen hin. Allerdings zeigte sich auch während des ersten Lockdowns eine Zunahme des Aktivitätsverhalten insbesondere bei Kindern und Jugendlichen in einigen wenigen Studien an. Sportarten und Intensitäten versänderten sich innerhalb der deutschen Bevölkerung während der Pandemie. Die Qualitätsbewertung der eingeschlossenen Studien ergab einen Mangel an adäquat berichteter gemessener körperlicher Aktivität sowie unzureichende Berichterstattung der Studienergebnisse.
- **Schlussfolgerung:** Die COVID-19 Pandemie hat zu einer Abnahme im Bewegungsverhalten in der deutschen Bevölkerung geführt. Angesichts der Ungewissheit über die Dauer der Pandemie sind anhaltende und behörden- und sektorenübergreifende Handlungen zur Förderung der körperlichen Aktivität in allen Bevölkerungsgruppen von entscheidender Bedeutung.

KEY WORDS:
Exercise, Sport, Lockdown, SARS-CoV-2

SCHLÜSSELWÖRTER:
Trainieren, Sport, Lockdown, SARS-CoV-2

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Introduction

Regular physical activity (PA) is associated with numerous health benefits, including the prevention and control of physical, mental and social health issues: Strong evidence shows that, par example, regular PA lowers the risk for cardiovascular diseases, diabetes, as well as breast and colon cancer (18). Besides, it has been suggested that an active lifestyle across the lifespan lowers all-cause mortality risk, independent of geographical location, socioeconomic status, and genetic predisposition (31). PA is further associated with improved mental health (49) and increased life expectancy (30).

However, in 2012 researchers called out the pandemic of physical inactivity (25), which is responsible for 5.3 million deaths per year worldwide (31) and is threatening the global economy. Despite multi-

Table 1

Inclusion and exclusion criteria for the rapid review.

	INCLUSION CRITERIA	EXCLUSION CRITERIA
Outcome	Investigation and quantitative analysis of changes (based on either prospective or retrospective designs) in physical activity (any type, domain or intensity; any measurement method) caused by the Covid19 pandemic	Study only focusses on physical activity behaviours during the pandemic without considering pre-pandemic behaviours (either prospective or retrospective)
		Studies focusing on sport club or fitness center membership rather than on physical activity behaviour
Population	Participants living in Germany were included.	Only participants with chronic diseases were included
	In case of international studies: data for the German participants are reported separately.	Studies among competitive/ professional athletes
		In case of international studies: no separate data analyses/presentation of German participants is available.
Publication type	Empirical studies published in English or German language	Commentaries/ discussion papers not presenting original data
		Publication language other than German or English

Table 2

Study characteristics.

CHARACTERISTIC	INCLUDED STUDIES, N(%)	SOURCES
PARTICIPANTS		
Children and adolescents	8 (25.8%)	(20, 26, 29, 33, 46, 47, 48, 58)
Young adults	6 (19.4%)	(8, 16, 19, 22, 40, 42)
Adults	17 (54.8%)	(3, 5, 10, 12, 13, 27, 28, 32, 34, 35, 37, 38, 39, 45, 51, 53, 55)
STUDY DESIGN		
Longitudinal study	12 (38.7%)	(5, 10, 28, 29, 34, 37, 38, 39, 46, 47, 48, 58)
Cross-sectional study	19 (61.3%)	(3, 8, 12, 13, 16, 19, 20, 22, 26, 27, 32, 33, 35, 40, 42, 45, 51, 53, 54)
PA INDICATOR		
WHO Guideline	10 (32.3%)	(12, 13, 19, 32, 33, 34, 46, 47, 48, 58)
Types of Sports	4 (12.9%)	(16, 42, 51, 54)
Types of PA	12 (38.7%)	(10, 12, 13, 28, 37, 38, 39, 45, 46, 47, 48, 58)
General PA	10 (32.3%)	(3, 5, 8, 16, 19, 20, 27, 29, 33, 40)
Step counts	1 (3.2%)	(22)
Reduction of PA	1 (3.2%)	(26)
Duration and Quantity of PA	3 (9.7%)	(22, 35, 51)
Inactivity	2 (6.4%)	(29, 33)
PA intensity	2 (6.4%)	(42, 53)
MEASUREMENT METHOD		
Questionnaire	31 (100%)	(3, 5, 8, 10, 12, 13, 16, 19, 20, 22, 26, 27, 28, 29, 32, 33, 34, 35, 37, 38, 39, 40, 42, 45, 46, 47, 48, 51, 53, 54, 58)
Smartphones	1 (3.2%)	(22)
SAMPLE SIZE		
<500	12 (38.7%)	(3, 16, 19, 20, 28, 29, 35, 42, 45, 51, 53, 54)
500-999	4 (12.9%)	(12, 13, 32, 40)
1000+	15 (48.4%)	(5, 8, 10, 22, 26, 27, 33, 34, 37, 38, 39, 46, 47, 48, 58)
REGIONAL CONTEXT		
National representative	11 (35.5%)	(10, 26, 32, 37, 38, 39, 42, 46, 47, 48, 58)
National	8 (25.8%)	(8, 12, 13, 19, 27, 51, 53, 54)
Regional	12 (38.7%)	(3, 5, 8, 16, 20, 22, 28, 29, 33, 34, 35, 40, 45)

ple efforts to tackle the physical inactivity crisis on multiple levels for several decades, more than 27% of the world's adult population fails to comply with the recommended 150 minutes per week of physical activity in 2020 (6). Furthermore, worldwide 81% of adolescents aged 11-17 years were insufficiently physically active in 2016 (17). In Germany, the prevalence of physical inactivity is equally alarming: prior to the pandemic, less than every 10th child (7) and only 42.6% of women and 48.0% of men (11) are meeting the WHO Global Guidelines on Physical Activity (55) that postulate a minimum level of PA required to offer significant health benefits and mitigate health risks.

Since January 2020, the outbreak of COVID-19 was declared a public health emergency and in March 2020, the outbreak of the virus was characterized as a pandemic (56). Many governments' immediate protective measurements aimed to halt, or at least slow down, the spread of the COVID-19 disease, which brought full or partial lockdowns of cities, travel bans and closed borders, social restrictions etc. (23). This drastic change in public and personal life brought changes to the population's lifestyle behavior. On many levels, the world population's daily PA has been impaired for months, affecting the health of a significant portion of the global society. Understanding how the COVID-19 pandemic impacted PA and related non-communicable diseases (NCDs) is to be completely understood, but we now know that the inactivity pandemic is key in the global explosion of NCD's that have tragically collided with the COVID-19 pandemic (21). Therefore, fighting the silent pandemic of physical inactivity and its health consequences is arguably one of the most pressing global public health challenges of the current and post-COVID-19 era.

Thus, the objective of this rapid review is to set the scene for PA changes of the German population in face of the COVID-19 pandemic. This review synthesizes empirical studies conducted in Germany.

Methods

Study Design

This research includes a rapid review strategy based on the standardized procedure proposed by Seidler, Nußbaumer-Streit (50). A rapid review approach has been conducted as it is an appropriate way to address health-related questions that require rapid answers during the COVID-19 pandemic (50).

Eligibility Criteria

Studies were included in the current review if they met various inclusion criteria regarding outcome, population, and publication type and if exclusion criteria did not apply (table 1).

Search Strategy

The database search was performed on 19 May 2022 using the electronic databases Pubmed and Web of Science (with all the databases included in this platform). The search strategy was based on the following search term: We used the filter for publication years (only 2020-2022) to refine the results. Additionally, we also screened all published articles of the journal collection of the German Journal of Exercise and Sport Research on "Physical activity, physical education, exercise and sport in times of the COVID-19 pandemic" that included 13 articles that were published in the bespoke journal from 01 January 2021 on https://link.springer.com/collections/efjfcffgji. Finally, we also conducted a hand search to identify all relevant articles.

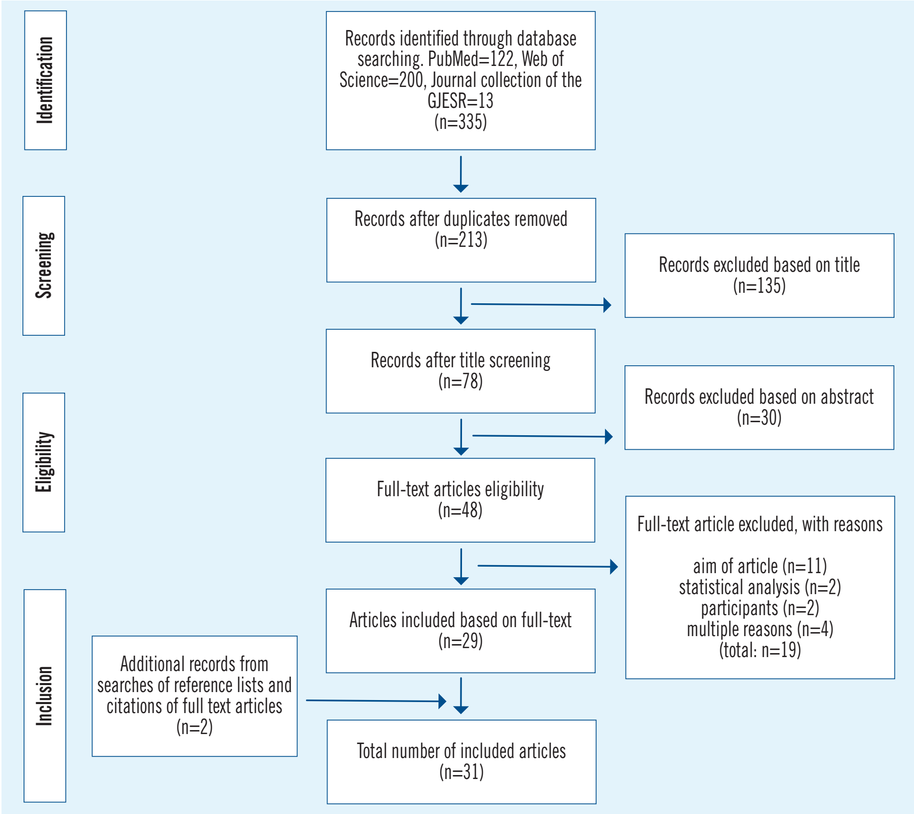

Figure 1

Flow chart summarising study selection and inclusion processes in this rapid review, including the reasons for exclusion of all full-text articles that were reviewed.

Study Selection and Data Extraction

Identified references were imported into Endnote X9, a reference management software (1). All duplicates were removed. This step was followed by a three-step study selection process, comprising (1) title-screening, (2) abstract-screening, and (3) full-text-screening for inclusion criteria by one researcher (F.B.). During each step of the screening process, all references that could not conclusively be excluded were kept for further screening in the next step. Insecurities in relation to final inclusion were resolved through discussion with a second researcher (A.K.R.). The following data were extracted from each included article: study title (if available) author(s); year; age of sample; sample size; regional context; study design; time points of measurement; measurement method; PA measures (PA indicator and units/categories/subgroups); prevalence of PA during the COVID-19 pandemic and changes in PA (decrease, no change, increase). All studies were also allocated to one of three ages categories (children and adolescents; young adults; adults).

Quality Assessment

We conducted a quality assessment following procedures as suggested by Brand, Nosrat (4) in their systematic review. This approach was based on criteria from the JBI checklist for analytical cross-sectional and prevalence studies (36), and the AXIS appraisal tool for cross-sectional studies (9). Included studies were rated along five categories about 1) aim of the study, 2) participants, 3) methods, 4) measures and 5) results. Each category was labelled with either "yes", "some concerns" and "no". To get a score for each individual study, we rated "Yes" with 2 points, "some concerns" with 1 point and "No" with 0 points. The maximum reachable sum score is 10 points.

Synthesis of Results

It was anticipated that the studies included in this rapid review would exhibit a diverse range of PA indicators and research methods, especially related to PA measures. Therefore, it was not appropriate to use meta-analysis to integrate and summarize the included studies. Instead, a narrative synthesis of results was performed. Findings of changes in PA prevalence were grouped based on age groups (children and adolescents, young adults and adults).

Results

A total of 335 potentially relevant articles were identified through database searches. After screening for titles and abstracts, full texts of 48 articles were retrieved for in-depth screening. 19 articles were excluded due to trivial aim of either the article, the statistical analysis, participants or other reasons, thus a total of 29 articles were identified as eligible and were included in this rapid review. Subsequently two additional publications were identified through hand search, yielding a total of 31 articles reporting on 23 unique studies included in this review (figure 1).

Characteristics of Included Studies

Overall, 23 projects, including 31 studies, were identified that investigated PA during the COVID-19 pandemic (March 2020-July 2021) in children and adolescents, young adults or adults from Germany (table 2) (table 3, 4, 5, see supplemental material online). Eight studies investigated PA changes in children and adolescents, six in young adults and thirteen in adults. PA indicators varied along the included studies, but the majority assessed WHO guideline compliance (N=10), types of PA (e.g., walking, gardening, outdoor play, unorganized PA) (N=12) or overall PA which was not described in greater detail (N=12).

Related to the study design, twelve studies assessed longitudinal data (5, 10, 28, 29, 34, 37, 38, 39, 46, 47, 48, 58) whereas the majority of identified studies (N=19) were cross-sectional in nature and 17 studies used retrospective data for reference. The remaining two studies (32, 53) compared the assessed data during the pandemic with existing data from similar studies (pre-pandemic). The sample size ranged from 106 (28) to 5,021 (8). In 11 studies, the sample was rep- ›

Table 6

Quality assessment of the included studies (based on JBI Checklist for analytical cross sectional and prevalence studies (34)).

SOURCE	AIMS/OBJECTIVES OF THE STUDY CLEARLY STATED?	MEASURE OUTCOMES (PA) CLEARLY DEFINED?	STATISTICAL RESULTS ADEQUATELY DOCUMENTED?	METHODS ADEQUATELY DOCUMENTED?	SCORE (YES=2; SOME CONCERNS=1; NO=0)
Brailovskaia, Truskauskaite-Kuneviciene (3)	Yes	Some concern	Some concerns	Yes	8/10
Brandl, Zimmermann (5)	Yes	Some concerns	Some concerns	Some concerns	7/10
Busse, Buck (8)	Yes	Yes	Some concerns	Yes	8/10
Engels, Mutz (10)	Yes	Yes	Yes	Yes	9/10
Fuezeki, Schroeder (12)	Some concerns	Some concerns	Yes	Yes	6/10
Fuezeki, Schroeder (13)	Some concerns	Some concerns	Yes	Yes	7/10
Giessing, Kannen (16)	Yes	Yes	Some concerns	Yes	8/10
Helbach and Stahlmann (19)	Yes	Yes	Some concerns	Yes	9/10
Hommes, van Loon (20)	Yes	No	No	Some concerns	4/10
Huber, Steffen (22)	Some concerns	No	Some concerns	Some concerns	3/10
Koletzko, Holzapfel (26)	Some concerns	No	No	Some concerns	3/10
Koopmann, Mueller (27)	Some concerns	No	Some concerns	Some concerns	4/10
Krist, Dornquast (28)	Yes	Some concerns	Some concerns	Yes	8/10
Kurz, Braig (29)	Yes	No	Some concerns	Yes	7/10
Maertl, De Bock (32)	Yes	Yes	Some concerns	Yes	9/10
Marckhoff, Siebald (33)	Yes	Yes	Some concerns	Some concerns	8/10
Mata, Wenz (34)	Yes	Yes	Some concerns	Yes	9/10
Mojtahedzadeh, Neumann (35)	Yes	Some concerns	Some concerns	Yes	8/10
Mutz and Gerke (37)	Yes	Yes	Yes	Yes	9/10
Mutz, Müller (38)	Yes	Yes	Yes	Yes	10/10
Mutz and Reimers (39)	Yes	Some concerns	Yes	Yes	9/10
Palmer, Bschaden (40)	Yes	Some concerns	Some concerns	Yes	7/10
Pietsch, Linder (42)	Yes	Some concerns	Yes	Yes	8/10
Schlichtiger, Steffen (45)	Some concerns	Yes	Yes	Some concerns	7/10
Schmidt, Anedda (46)	Yes	Yes	Yes	Yes	10/10
Schmidt, Burchartz (47)	No	Yes	Some concerns	Yes	5/10
Schmidt, Burchartz (48)	Yes	Yes	Yes	Yes	10/10
Sonza, da Cunha de Sá-Caputo (51)	Some concerns	No	Some concerns	Some concerns	5/10
Tschuschke and Schröder (53)	Yes	Some concerns	Some concerns	Some concerns	6/10
Wendtlandt and Wicker (54)	Yes	Yes	Some concerns	Yes	7/10
Wunsch, Nigg (58)	Yes	Yes	Some concerns	Yes	8/10

resented by a nationwide representative sample (10, 26, 32, 37, 38, 39, 42 46, 47, 48, 58) whereas the remaining 20 studies took place either across Germany (N=8) (8, 12, 13, 19, 27, 51, 53, 54) or in a regional context within Germany (N=12) (3, 5, 8, 16, 20, 22, 28, 29, 33, 34, 35, 40, 45).

Evidence on Changes in PA Prevalence

Children and Adolescents

PA levels in children and adolescents increased during the first lockdown in Germany in the MoMo-Study (46, 48, 58) and less children and adolescent were classified as physically inactive (29). Other studies indicated for the same time period lower PA levels in children (20, 26), especially in older children and adolescents (26). The trend towards lower PA levels in older children and adolescents was equally identified in the subsequent MoMo-Study in which data was collected during the second lockdown in Germany (December 2020-May 2021) (47) (table 3, see supplemental material online).

Young adults

The change of compliance with the WHO guideline was assessed in one study for young adults and indicated a small decrease (37.4% to 36.8%) (19). A change in the types of sports has been observed, which is associated with a change towards types of sports that can be done without others (e.g., jogging, gymnastic and strength training at home, unorganized sports) (16, 42). Regarding PA intensities, the amount of PA with low and moderate intensities increased in this age group during the first and second lockdown (8, 42) (table 4, see supplemental material online).

Adults

Percentage of adults meeting the WHO guideline decreased since the onset of the pandemic (12, 13, 34). However, Maertl, De Bock (32) indicated an increase from 29.4% to 32.1% of adults achieving the PA recommendations. Overall, PA as well as the amount of PA in some types (e.g. walking, active travel, gardening...) decreased (10, 12, 13, 27, 28, 37, 38, 39, 45). Similar to trends observed in young adults, PA with lower intensities increased or did not change while PA with higher intensities decreased during pandemic in adults (5, 53). There was also a change in the types of sports (51, 54); aerobic training increased while strength training decreased (51) (table 5, see supplemental material online).

In addition to the quantitative changes in PA that occurred during the pandemic, one further aspect has been observed: there were changes regarding the way how people exercised during the pandemic. For example, Mutz, Muller (38) examined the use of digital media for home-based activities during the COVID-19 pandemic and found that 23% of adults in Germany having used digital media for sports activities at least once during the pandemic while public and private sports infrastructure were closed. A variety of digital exercise options were used, especially in younger, higher educated and financially better situated participants. People using digital tools to engage in exercise reported 30min/week more time in exercise activities during the pandemic compared to individuals who solely exercised without digital media.

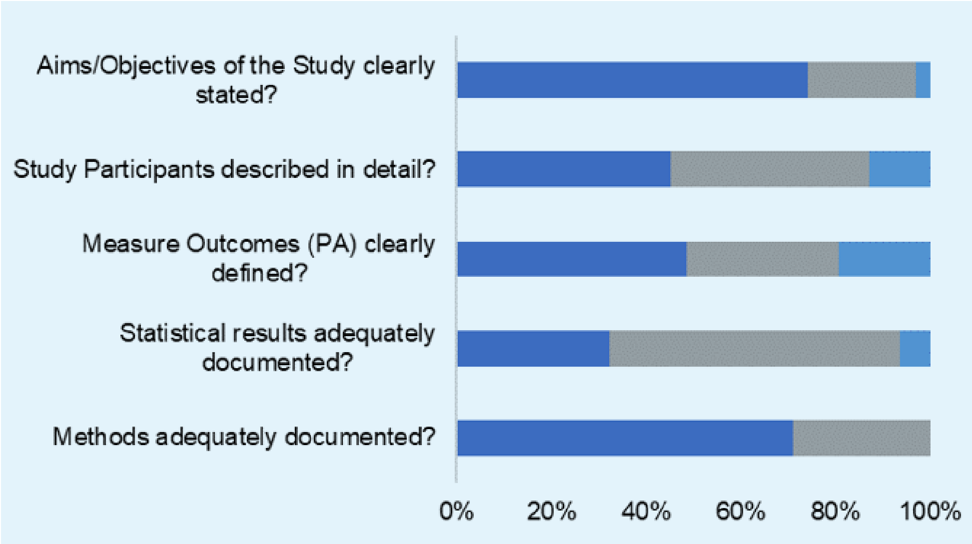

Figure 2

Standardized assessment of methodological quality. Dark blue=yes, grey=some concerns, light blue=no.

Quality Assessment

The results of the standardized assessment of the methodological study quality using two standardized instruments is summarized and can be found in figure 2. The results of this evaluation show that 70.9% of the included studies (N=22 studies on PA behavior change) are lacking quality in two or more domains. Many studies had no clear description of the assessed PA (51.6%). In particular, it was not clear, what type or domain of PA (e.g. structured vs. unstructured) was investigated. Furthermore, studies lacked related to sufficient reported results by missing key statistical analysis such effect sizes, p-values or test-results. In 10/31 of the included studies statistical results were documented adequately and sufficiently. Overall, the sum score of the included studies reached a mean value of 7.1/10 points with the lowest quality in Huber, Steffen (22) and Koletzko, Holzapfel (26) with only 3 of 10 points. On the other hand, three studies had the highest possible sum score of 10 points (38, 46, 48) (table 6) (table 3, 4, 5, see supplemental material online).

Discussion

Since the onset of the COVID-19 pandemic, PA opportunities have been restricted for the majority of the population due to lockdown measures, including closures of sport grounds, sport clubs and schools, and the quarantine and social distancing measures implemented by many countries worldwide. Several reviews summarized the changes of PA from pre to during the lockdown in countries all over the world (4, 41, 52, 57). As restrictions to slow down the spread of the virus varied across the countries, it is challenging to compare the changes in PA levels (2). Thus, the aim of the present rapid review was to summarize the PA changes from pre to during the pandemic in the German population.

This rapid review identified 31 suitable studies. The majority of these studies reported that PA declined during the first and second COVID-19 pandemic lockdown, regardless of the target population or the methodology used. Nevertheless, half of the studies with children and adolescents revealed increases in PA levels during the first lockdown (29, 46, 48, 58). This could be explained by the closure of kindergartens and schools resulting in more recreational time to engage in unorganized PA (43). Additionally, the first lockdown took place during spring in Germany. Coming from winter, rising temperature levels invited many to be physically active outdoors (14, 15). On the other hand, decreases of PA in children and adolescents can be explained by the closure of sports clubs and thus restricting one important opportunity to engage in PA (44). These contradictory findings could be transferred to different PA indicators that were measured as well as different time points of the COVID-19 pandemic. In (young) adults, data indicated predominantly a decrease of PA levels during the pandemic. This reduction of PA in (young) adults could be explained by the closure of sports club and other social restrictions.

Furthermore, data indicated a change in the types of sports people engaging in. In particular, an increase was seen in aerobics, jogging, and strengthening training (16, 42, 51) with a shift from strengthening in a gym/sports club to strengthening on their own or with digital media (38, 42). Lockdown measures (especially the closure of sports clubs (44)) may be the reason for this change in types of sports. It seems that those types of sports flourished where no kind of equipment is needed and which can be done at home. For future pandemics, it would be helpful to advance the levels of digital exercise opportunities and make it accessible to all age groups.

Lastly, besides the change in the types of sports, included studies indicated a shift from high intensity to lower intensity, especially in young adults and adults (5, 8, 42, 53). This could be explained by the types of PA people engaged during the lockdown. Activities such as walking, bicycling and other light intensity activities tend to substitute high-intensity sport (37).

Taken together, included studies revealed predominantly a decline in PA from pre to during the COVID-19 pandemic in the German population with shifts in types of sports and intensities. Nevertheless, as our data extraction showed, PA indicators as well as the measured units or categories are quite › heterogeneous (e.g. WHO guideline, type of PA, type of sports, reduction/change of PA, intensity/frequency…). This heterogeneity makes it difficult to synthesize and compare the different findings. Despite this strong regional and methodological heterogeneity, our results seem to be in line with similar reviews including studies from around the world (4, 41, 52, 57).

Besides the methodological heterogeneity, included studies also differ vastly in quality assessment. This can also be seen in other reviews summarizing the changes of PA levels during the pandemic (4, 57). Especially, only one-third of included studies defined PA measure outcomes clearly, which could be responsible for the great heterogeneity in the used PA indicators in this rapid review. A clearer definition would help to narrow down few PA indicators.

Strengths and Limitations

The first strength of the present rapid review is the inclusion of studies investigating changes of PA levels from pre to during COVID-19 among all age groups (children, adolescents, young adults, as well as adults). A further strength of the study is that only data from Germany was included, which enables an analysis of changes in the German population that might be different to other populations. In addition, our rapid review included 12 longitudinal studies, which are more reliable to assess changes from pre to during the pandemic in Germany compared to retrospective data.

Nevertheless, this review has some limitations. First, the methodology used to measure PA were highly heterogeneous, making direct comparison of respective results difficult. Moreover, many studies used retrospective data for the pre COVID-19 data and thus, the accuracy of the reported data may be questionable. Another limitation is the representativeness of the included studies. Many of the studies were conducted in one region and thus are not representative for the German population. Lastly, we only included healthy participants and did not focus on vulnerable groups that might be particularly affected by the pandemic.

Conclusion

This rapid review aims to provide an overarching and holistic picture of PA prevalence changes in Germany during the COVID-19 pandemic from 2020-2021. The included studies revealed that PA levels predominantly decreased within the German population, even if few studies indicated an increase of PA levels in children and adolescents during the first lockdown. Overall, the COVID-19 pandemic seems to reinforce the existing PA inactivity among the population, also referred to as the pandemic of physical inactivity (24). Despite the lack of some quality criteria in the included studies, our conclusion is clear: for future pandemics, restriction policies need to be adapted. In particular, children as well as adults need to be provided sophisticated information about the importance of sufficiently PA especially in specific times of lockdowns. We now know that in times of self-isolation, physical and social restrictions, PA must receive higher priority by decisive stakeholders (e.g. policy makers, school teachers, employers etc.) so that further reductions in PA levels can be avoided and optimal health can be maintain or even enhanced. We suggest that a combination of the provision of PA opportunities for all, mass media campaigns on the health benefits of PA and multisectoral work is key in assisting the population maintain PA levels during future pandemics. Further research should focus on the influence of COVID-19 on PA levels among vulnerable groups, as these groups are neglected so far in existing reviews.

Conflict of Interest
The authors have no conflict of interest.

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Körperliche Aktivität während der COVID-19-Pandemie: Veränderungen in der Prävalenz körperlicher Aktivität in Deutschland

Physical Activity in the Face of the COVID-19 Pandemic: Changes in Physical Activity Prevalence in Germany

ERWEITERTES ABSTRACT

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Aufbau des Papers

Körperliche Aktivität ist eine wichtige Komponente zur Förderung der körperlichen und geistigen Gesundheit und zur Prävention von Krankheiten. Die COVID-19 Pandemie und die damit einhergehenden Maßnahmen führten zu entscheidenden Veränderungen im täglichen Leben der Bevölkerung und damit auch im Bewegungsverhalten. Diese Arbeit fasst die aktuelle Literatur über die Veränderung der körperlichen Aktivität während der COVID-19-Pandemie in der deutschen Bevölkerung zusammen.

Literatur

Als Grundlage dienen Untersuchungen und quantitative Analysen von Veränderungen der körperlichen Aktivität im Verlauf der COVID-19 Pandemie. Dabei werden empirische Studien von Kinder und Jugendlichen und auch Erwachsenen aus Deutschland einbezogen.

Ergebnisse und Diskussion

Die Ergebnisse deuten überwiegend auf einen Rückgang der körperlichen Aktivität in allen Altersgruppen hin. Dieser Rückgang könnte durch die Schließung von Sportvereinen und anderen sozialen Einschränkungen erklärt werden. Allerdings zeigte sich auch während des ersten Lockdowns in wenigen Studien eine Zunahme des Aktivitätsverhalten, insbesondere bei Kindern und Jugendlichen. Dies könnte auf die vermehrte Freizeit aufgrund von Schul- und Kindergartenschließungen zurückzuführen sein. Außerdem veränderten sich Sportarten und Intensitäten während der Pandemie. Die Qualitätsbewertung der eingeschlossenen Studien ergab einen Mangel an adäquat berichteter gemessener körperlicher Aktivität sowie unzureichende Berichterstattung der Studienergebnisse.

Was ist neu und relevant?

Die Übersichtsarbeit zeigt die Veränderungen der körperlichen Aktivität bei Kindern, Jugendlichen und (jungen) Erwachsenen in Deutschland im Verlauf der COVID-19 Pandemie auf.

Methodische Einschränkungen

Die verwendete Methodologie in den eingeschlossenen Studien war sehr heterogen, was einen direkten Vergleich der einzelnen Studien schwierig macht. Außerdem haben viele Studien retrospektiv die Pre-COVID-19 Aktivitätslevel erfasst, was die Genauigkeit der berichteten Daten etwas in Frage stellt. Viele eingeschlossene Studien sind außerdem eher regional und damit nicht repräsentativ für Deutschland.

Schlussfolgerungen für die Praxis

- Sowohl Kinder als auch Erwachsene müssen differenziert über die Bedeutung einer ausreichenden Bewegung informiert werden, insbesondere in Zeiten von Pandemien
- Um eine weitere Verringerung der körperlichen Aktivität zu vermeiden und eine optimale Gesundheit zu erhalten oder sogar zu verbessern, muss körperliche Aktivität von den entscheidenden Interessengruppen (z. B. politischen Entscheidungsträgern, Lehrern, Arbeitgebern usw.) eine höhere Priorität eingeräumt werden.
- Eine Kombination aus der Bereitstellung von Bewegungsmöglichkeiten für alle, Massenmedienkampagnen über die gesundheitlichen Vorteile von Bewegung und Sektor übergreifender Arbeit kann der Schlüssel zur Unterstützung der Bevölkerung bei der Aufrechterhaltung des körperlichen Aktivitätsniveaus während zukünftiger Pandemien sein.

QR-Code scannen und Artikel online lesen.

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Summary

The present review summarized the impact of the Covid-19 pandemic, respectively, the measures that were implemented during the pandemic on PA levels across German children and adolescents. The imposed measures lead to perturbations of the habitual living and activity behavior. In the case of the restrictions, our rapid review indicated predominantly a decline in PA amongst all age groups. As the thesis focuses on children and adolescents, findings of this age group are discussed in more detail. PA levels in children and adolescents (*N*=8 studies) increased in one study predominantly during the first lockdown (Schmidt et al., 2020a). However, other studies indicated a decrease of PA levels in children and adolescents during the Covid-19 pandemic (Hommes et al., 2021; Koletzko et al., 2021; Schmidt et al., 2021). Further, types of sports and intensities changed within the German population during the pandemic. In summary, this review illustrated the impact of changes on the policy level variables on the habitual PA behavior in children and adolescents in Germany.

3.2 Stability – Biological Basis of Physical Activity and ActivityStat Hypothesis

As seen in the previous chapter, there is a huge range of factors that could lead to a perturbation of the habitual behavior and is thus followed by changes in the habitual PA levels. Therefore, these changes end up in variability of PA levels by impacting the stability of habitual activity behavior. Nevertheless, in the context of PA, the issue of stability of PA is particularly relevant from a public health perspective as epidemiological studies highlight that continuous and stable activity behavior reduces the risk of coronary heart disease and other health risks (see chapter 2.2) (Hernelahti et al., 2004; Twisk et al., 2000).

There is a mechanism focusing on biological control that leads to stability of activity behavior by compensation (Rowland, 1998). The activity compensation that is based on the ActivityStat hypothesis, suggests that increases in PA at one time point/in one domain might induce decreases in PA at another timepoint/in another domain, and vice versa, in order to maintain a stable energy level over time (Rowland, 1998). Based on this concept individuals maintain their total PA at a constant level by adapting various mechanisms, such as increasing or decreasing the frequency, intensity, or duration of time spent engaged in PA. By such adapting mechanisms, their actual energy expenditure can either be increased or decreased so that the overall energy expenditure is stable over a certain period of time (see Figure 6).

Merging variability and stability could mean that changes in the different levels (i.e., based on the social-ecological model) surrounding an individual will lead to perturbations in the (habitual) activity behavior (variability). Following the ActivityStat hypothesis, this leads to compensatory behavior resulting in a stable activity level. Nevertheless, less knowledge exists about behavior following deviations greater than the habitual variability (±20-25%) (see Figure 3). Following the ActivityStat hypothesis, activity compensation should occur. In Figure 6, potential responses after perturbations (long- and short-term) greater than ±20-25 % of the habitual behavior are illustrated.

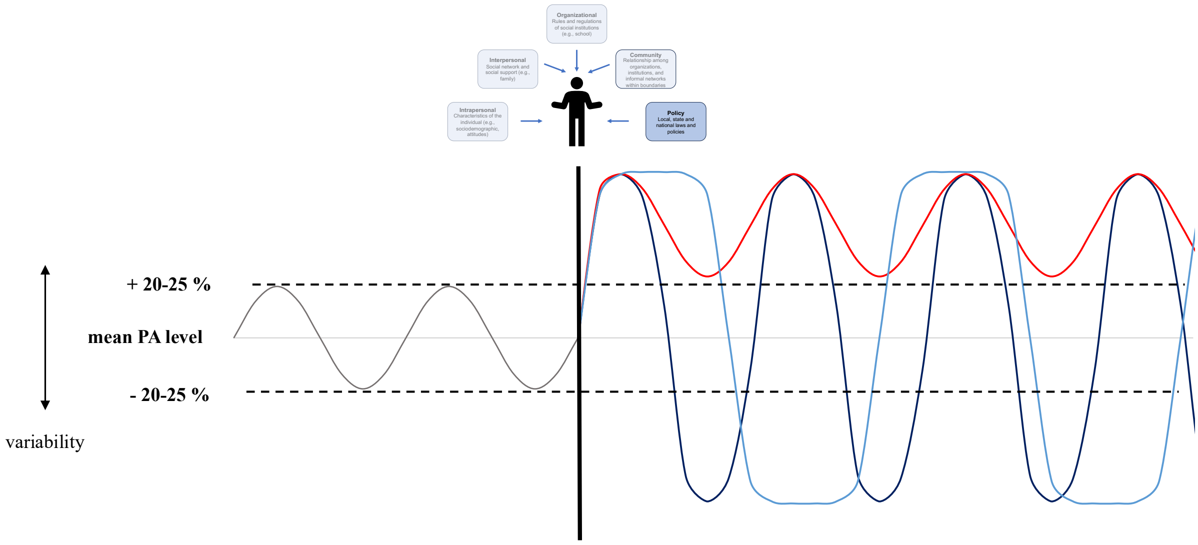

Figure 6: Schematic illustration of habitual activity variability ranging from +20-25% to -20-25% (left) and how the subsequent behavior change looks like after a perturbation within one's environment (e.g., changes in the policy level) (right).

*Note: : ------- represents the threshold for intra-individual variability (Eisenmann & Wickel, 2009). Dark blue represents a compensatory behavior after a short-term change following a perturbation (negative compensation). Light blue represents a compensatory behavior after a long-term change following a perturbation (negative compensation). The red line illustrates no compensation, e.g., PA level is overall increased as it does not decrease after the deviation from the habitual behavior.

As seen in Figure 5 and in chapter 3.1, deviation could be an increase or a decrease and thus, the following compensatory response occurs in the contradictive direction. For better understanding, we differ between a positive and a negative activity compensation. Positive compensation is stated as the increase of activity after a reduction in overall activity; in other words, healthful compensation as it helps avoiding a reduction of overall PA levels. In contrast, 'harmful' or negative compensation means that an increase of activity is followed by a decrease of activity at another timepoint, avoiding an increase of overall PA levels (Beck et al., 2022b; Swelam, 2022).

To illustrate and distinguish between positive and negative activity compensation, two examples are given to explain how activity compensation could occur. On a day when a child has physical education (PE) at school, the child may experience an increase in PA in the morning compared to a day without PE lesson. However, the child may subsequently increase the time that it spends being sedentary in the afternoon (negative compensation), resulting in an overall PA level that is not increased for this day (see Figure 7).

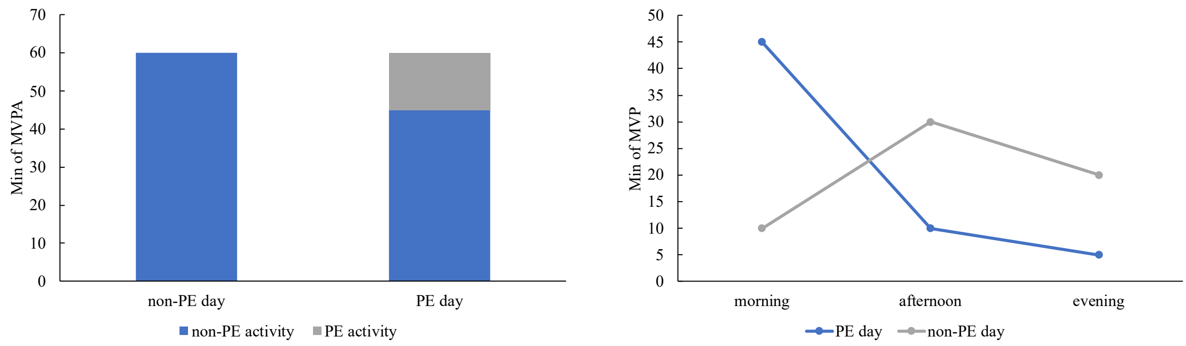

Figure 7: PE-Day and non-PE day illustrate compensatory behavior within one subject. In the left figure the stable PA behavior is shown. Increase of PA on a PE day in the morning and decrease of PA level in the afternoon is presented in the right figure.

In contrast, positive compensation may occur when training in the afternoon was shorter than usual, and children will then subsequently compensate this perturbation, e.g., lack of PA, by a PA increase compared to the habitual behavior (Figure 8).

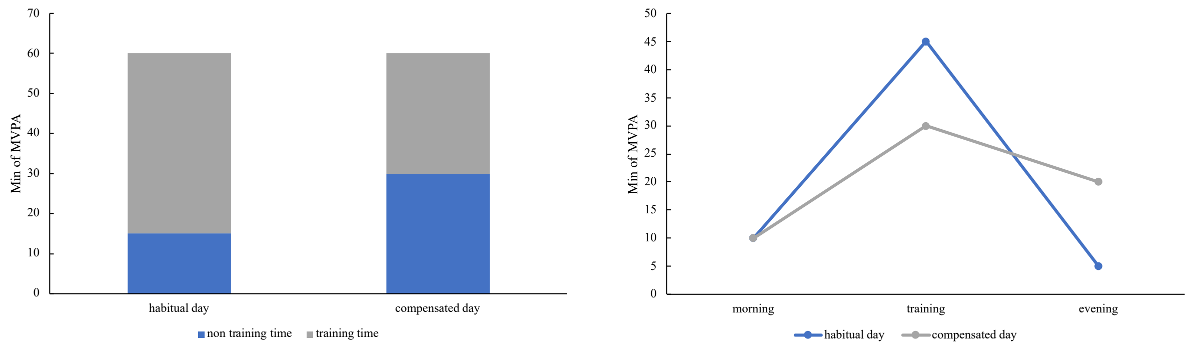

Figure 8: Habitual day and a compensated day. Left illustrates the PA minutes for a habitual day and on a day with less training time. In the right figure the stable PA behavior is shown.

Transferring compensatory behavior to the context of intervention efficiency, this means that interventions merely create a perturbance in daily PA levels that results in increases of PA levels during the intervention. However, after the disruption is removed (e.g., exposure of intervention) PA levels typically return to baseline (Wilkin, 2011; Wilkin et al., 2006). This could be a potential explanation of inefficacy of interventions. Nevertheless, this has largely been ignored, even there was evidence for a potential effect on overall PA over 20 years ago (Eisenmann & Wickel, 2009; Gomersall et al., 2013; Rowland, 1998). A meta-analysis of school-based interventions indicated that in intervention time, PA increased, whereas regarding the whole day, there is no evidence of an effect of the intervention (Jones et al., 2020). Thus, habitual PA was decreased at timepoints outside the intervention, following in stability of PA levels of the participants. As a result, there is no difference in PA levels between a day with and without intervention (Aburto et al., 2011). In this context, negative activity compensation occurs.

In the following paragraphs the underlying ActivityStat hypothesis and the associated components will be explained in more detail.

3.2.1 The ActivityStat Hypothesis

The ActivityStat was first introduced by Rowland (1998) over 20 years ago as a hypothesis proposed to explain how activity compensation may function. Whilst the underlying mechanisms are not fully understood until now, it is hypothesized that the ActivityStat is a biological feedback (i.e., homeostatic) mechanism responsible for regulating (i.e., compensating) activity (Rowland, 2016). The ActivityStat appears to function as a central control mechanism for sustaining PA over time. It can be compared with other homeostatic mechanisms that regulate body temperature, blood pH, glucose levels, and fluid balance (Rowland, 1998, 2016). This may be an explanation for the difficulty to sustainably change PA levels over time.

The ActivityStat is thought to impact activity through a neuro-humoral feedback loop within the central nervous system. This loop operates in continuous cycles regulated by muscle tissue receptors and is tied to the activity set-point in the hypothalamus. In this context, the hypothalamus, responsible for various homeostatic mechanisms like fluid balance, temperature, and caloric intake, serves as the base for this regulatory process (Wilkin et al., 2006). The main aim of the ActivityStat is to maintain a balance where the level of PA output aligns with its established set-point (Wilkin, 2011).

3.2.2 Activity Set-point and Tolerance

A central component of the functionality and elasticity of the ActivityStat is the activity tolerance which is oriented towards an innate set-point value. Similar to other homeostatic mechanisms such as temperature regulation and blood pH, there exists a threshold of stimulus that the body can tolerate before adjusting itself to return to its set-point (Gomersall et al., 2013). To illustrate, in temperature regulation, a small drop from 22°C to 21°C may not prompt the instinct to put on a jacket. In this case, the level of tolerance has not been exceeded as the change is quite small, triggering a homeostatic response is unlikely. However, larger drops (e.g., 22°C to 12°C) may result in observable behavioral changes such as putting on extra layers of clothing, or physiological changes, such as shivering (Swelam, 2022). The concepts of set-point and tolerance are applicable in the context of activity levels within the ActivityStat hypothesis, as evident when examining prolonged periods of standing. For example, a person may comfortably stand for 20 minutes, but if he or she persists in standing for several hours, such as during a shopping trip or teaching in a class, he or she might reach a point where the need to sit emerges, indicating that he or she has reached their tolerance threshold (King et al., 2007; Schutz et al., 2014).

As discussed earlier, the core idea of the ActivityStat hypothesis and, consequently, the biological control of PA, is to maintain a state of equilibrium (Rowland, 2016). To do so, it is essential that the feedback mechanism operates around an innate set-point. Concerning the ActivityStat, it appears that there is a certain degree of variability and flexibility (i.e., tolerance) associated with this set-point (Gomersall et al., 2013; Rowland, 2016). This becomes plausible when considering other corrective movements in daily life that contribute to overall stability. Rowland (2016) uses the example of "…minor repetitive corrective alterations of movements of one's hands on the steering wheel to keep an automobile headed straight in the lane. Quite paradoxically, it would seem, stability requires variability" (Rowland, 2016) (pp. 118).

Additionally, it's important to note that there is a level of between-person variability in both an activity set-point and tolerance, as individuals engage in different levels of activity. As mentioned above (chapter 3.1), intra-individual variability in children and adolescents' activity lies around ±20-25% (Eisenmann & Wickel, 2009; Levin et al., 1999). Thus, it is hypothesized that the ActivityStat set-point may be flexible and dynamic; varying for example with individual variability, season, age or energy intake (Gomersall et al., 2013). Therefore, it could be argued that for a compensatory response to occur, a perturbation would need to induce an at least ±20% deviation from one's habitual PA level within a given timepoint of interest, with compensatory responses occurring within- and/or between-day(s) in accordance to weekly activity cycles (Swelam, 2022).

3.2.3 Timespan of Potential Compensatory Responses

If compensatory behavior occurs, the timespan at which an ActivityStat would return to the set-point is unknown, with the possibility of compensatory responses occurring within and/or between-days, or over longer periods of time such as weeks or years. Gomersall et al. (2013) proposed that the compensation timespan is directly linked to the lag time of the response curve and thus, it is unlikely that an ActivityStat would occur within an hour or even a day; rather the process may take weeks or months. However, understanding the timespan of potential compensatory responses is crucial for practical reasons, guiding methodological decisions related to study design, frequency of measurement and the duration of the intervention (Gomersall et al., 2013).

3.3 Purpose and Aim of the Dissertation

The current state of research presented in the previous chapters illustrated the promising role of PA for the health status of children and adolescents. However, PA levels are insufficient and health promotion efforts seem to miss their goal. A deeper focus on PA in the context of variability highlighted the different influencing factors as well as the resulting variability of PA behavior (including **Manuscript A**). Furthermore, the impact of the biological control postulates a stable level of PA in children and adolescents (ActivityStat hypothesis), but is barely investigated and understood. Thus, current gaps in knowledge and open questions need to be addressed to highlight variability and stability in the context of compensatory behavior of PA in children and adolescents before the overarching aim of developing and implementing evidence-based effective interventions to promote PA can be considered. In more detail, to address the gaps in terms of compensatory behavior, we use different approaches concerning measurement methods.

Beginning with device-based measurement methods, providing accurate measurements and quantified values, **Manuscript B** will firstly illustrate validation and calibration of an accelerometer for children and adolescents. Following, based on the knowledge about advantages of device-based measurement tools, we try to gain a comprehensive and deeper understanding of the current evidence around compensation by conducting a systematic review (**Manuscript C**) and focusing in **Manuscript D** on exploration of (pre)adolescents' activity compensation by taking sociodemographic data into account. As subjective measurement tools allow insights into the behavioral context of activity compensation as well as perception and influencing factors, subjective measurement tools can be helpful to gain a deeper understanding of activity compensation. Thus, to explore and understand activity compensation in a deeper way, including perception and influencing factors in adolescents, we conducted **Manuscript E** and lastly the found information about compensatory behavior are illustrated by transferring them on a real example (Covid-19 pandemic) (**Manuscript F**).

4 Compensation of Physical Activity in Children and Adolescents in the Public Health Context

Activity compensation is identified as a biological control mechanism to maintain a stable PA level (Rowland, 1998) and is scarcely understood. Within the following chapters, we tried to answer open questions and to contribute to a holistic understanding of activity compensation by focusing on two different measurement approaches.

4.1 Activity Compensation Based on Device-based Measurement Methods

First of all, to assess PA, respectively activity compensation, there is a need for reliable and valid measurement tools. To gain first insights into activity compensation, device-based approaches that rely on measuring physiological or biomechanical variables to generate a quantifiable assessment of activity outcomes, encompassing energy expenditure (Corder et al., 2008; Ridgers & Fairclough, 2011) seem to be helpful. In general, there exist a variety of device-based measurement tools, that could be used for measuring and estimating energy expenditure or time spent in the various activity intensities. The most common used device-based methods in the field of PA are accelerometry, pedometry, heart rate monitoring, direct observation, indirect calorimetry, and doubly labelled water (Dollman et al., 2009; Hardy et al., 2013). The quantification of activity results in PA and SB estimates that exhibit high reproducibility and minimal bias, yet are not entirely devoid of error (Reilly et al., 2008). In particular, device-based measurement methods are in the critic to underestimate the PA levels (Tarp et al., 2014).

Device-based measurement methods provide numerical data of activity variables for interpretation and therefore, provide the opportunity to understand the relationships between activity and health outcomes in a more quantifiable way (Reilly et al., 2008). What kind of device-based method to assess PA levels in children and adolescents should be chosen depends on factors surrounding the respective study (Dollman et al., 2009), including the participants' age, sample size, timeframe of assessment, data management options, and margin of measurement error associated with the approach (Dollman et al., 2009; Hills et al., 2014).

Doubly labeled water (the so called "gold standard") and indirect calorimetry (Mtaweh et al., 2018; Westerterp, 2017) are recognized as accurate methods for measuring PA levels but are limited by their high cost and lack of time-stamped data, making them impractical for population-level studies (Sirard & Pate, 2001; Trost, 2007). In contrast, heart rate monitors, pedometers, and accelerometers offer cost-effective and less burdensome alternatives for collecting data from larger samples (Barkley et al., 2019). However, traditional pedometers cannot differentiate between different movement patterns (Strath et al., 2013; Trost, 2007), while heart rate monitors may be influenced by external factors such as temperature, stress, and anxiety (Corder et al., 2008; Hills et al., 2014). Accelerometers are commonly used by researchers to assess children's free-living activity (Burchartz et al., 2021; Migueles et al., 2017; Sallis & Saelens, 2000; Schneider et al., 2004).

As accelerometry is one important and common measurement tool to assess compensatory behavior (chapter 4.1.2 and 4.1.3), this approach should be described in more detail. Before compensatory behavior can be assessed with such devices, there is a need for calibration. Thus, the calibration of one accelerometer for children and adolescents will be illustrated before (chapter 4.1.1).

Accelerometry

Accelerometers are wearable devices used to monitor activity in ‘real time’ by detecting body accelerations through movement, detecting movement in one (uniaxial; e.g., vertical), two (biaxial; e.g., vertical and mediolateral) or three planes (triaxial; e.g., anterior-posterior, vertical, and mediolateral) (Dollman et al., 2009; Ridgers & Fairclough, 2011; Strath et al., 2013). As most accelerometers are triaxial, this makes a quantification of the intensity, frequency and duration of an activity possible, in contrast to just counting steps (Oliver et al., 2007; Pate et al., 2010; Reilly et al., 2008; Sirard & Slater, 2009). Overall, accelerometers can be worn on different body positions such as hip, wrist, chest, or thigh. The most common used are hip worn accelerometers, that reveal accurate classification of activity type and correct classification of PA intensities (Lyden et al., 2014; Montoye et al., 2015; Staudenmayer et al., 2009). Nevertheless, there are advantages of wearing accelerometers on other body locations (e.g. improved comfort) (Montoye et al., 2015).
Accelerometers are relatively cheap compared to direct observation or indirect calorimetry (Strath et al., 2013). They also have low participant burden with their small size, making them discreet, and practical for measuring children’s PA and sedentary time (Trost, 2007). One notable advantage of utilizing accelerometers lies in their precision, dependability, validity, and practicality when assessing activity, in both laboratory (Hager et al., 2016; Trost et al., 1998) and free-living conditions (Ott et al., 2000), particularly amongst children (Corder et al., 2008; Reilly et al., 2008).

Nevertheless, there is a discussion about analysis of accelerometer data. There is ongoing debate about the most appropriate approaches (Migueles et al., 2017). New approaches to data analysis are emerging, shifting away from count-based methods to instead focus on the examination of raw acceleration (e.g., intensity gradient, average acceleration (Rowlands et al., 2018), Monitor-Independent Movement Summary unit [MIMS-unit] (John et al., 2019), or cut-off points to acceleration data (e.g., Euclidean Norm Minus One [ENMO] (Bakrania et al., 2016), Mean Amplitude Deviation [MAD] (Bakrania et al., 2016)). Overall, cut-off points are generated to define the time spent in activity intensities within a given epoch length or raw acceleration data (Ridgers & Fairclough, 2011).

For any given type of accelerometer, cut-off points need to be determined using a calibration and validation study (Ekblom et al., 2012; Evenson et al., 2008; Sun et al., 2008; Van Cauwenberghe et al., 2011). This determination is complex and not without limitations (Ridgers & Fairclough, 2011; Trost et al., 2011). In the past, cut-off points were derived through continuous walking and running protocols conducted in laboratory settings, providing a controlled environment for managing PA intensities and measuring energy expenditure, often through methods like indirect calorimetry (Sirard & Pate, 2001).

Nevertheless, more and more studies used free-living conditions to better simulate the different types of activities that children engage in (Montoye et al., 2016; Puyau et al., 2002; Treuth et al., 2004; Welk, 2005).

Moreover, in the initial stages, cut-off points for children's activities were established based on typical adult thresholds (Sallis et al., 1991). However, this approach proved inappropriate due to variations in body structures (such as weight, leg length, and height) and, consequently, differences in locomotion (e.g., the number of steps taken within a given epoch length) (Sallis et al., 1991). Consequently, using adult cut-off points for children leads to a systematic underestimation of activity, with observed discrepancies ranging from 5% to 40% (Sallis et al., 1991). Subsequently, it was recommended that age-specific cut-off points need to be implemented to mitigate this risk (Migueles et al., 2017), and taking into account the specific characteristics of the population group under study (Ridgers & Fairclough, 2011). In the following chapter, a calibration and validation of an accelerometer for children and adolescents will be illustrated.

4.1.1 Manuscript B: Determination of Cut-off points for the Move4 Accelerometer in Children Aged 8-13 Years

Beck, F., Marzi, I., Eisenreich, A., Seemüller, S., Tristram, C., & Reimers, A. K. (2023). Determination of cut-off points for the Move4 accelerometer in children aged 8–13 years. *BMC Sports Science, Medicine and Rehabilitation, 15*(1). https://doi.org/10.1186/s13102-023-00775-4

Introduction

To assess PA levels for children and adolescents in an appropriate way, it is necessary to determine cut-off points for children as their body structures and thus, locomotion is not equal to adults (Sallis et al., 1991). Thus, as a part of the present thesis, cut-off points for the Move4 accelerometer from Movisens were determined for children aged 8-13 years. For this, a test-retest study design was conducted, with participants wearing four sensors (hip, chest, thigh, arm) while performing nine activities that covered four intensity level. The chosen activities were validated with respect to their intensity level by using the heart rate and cut-off-points were determined for all sensor positions.

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RESEARCH
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Determination of cut-off points for the Move4 accelerometer in children aged 8–13 years

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Abstract

Background To assess physical activity (PA) there is a need of objective, valid and reliable measurement methods like accelerometers. Before these devices can be used for research, they need to be calibrated and validated for specific age groups as the locomotion differs between children and adults, for instance. Therefore, the aim of the present study was the calibration and validation of the Move4 accelerometer for children aged 8–13 years.

Methods 53 normal weighted children (52% boys, 48%girls) aged 8–13 years (mean age = 10.69 ± 1.46, mean BMI = 17.93 kg/m^{-2}, 60th percentile), wore the Move4 sensor at four different body positions (thigh, hip, wrist and the Move4ecg including heart rate measurement at the chest). They completed nine activities that considered the four activity levels (sedentary behavior (SB), light PA (LPA), moderate PA (MPA) and vigorous PA (VPA)) within a test-retest design. Intensity values were determined using the mean amplitude deviation (MAD) as well as the movement acceleration intensity (MAI) metrics. Determination of activities and energy expenditure was validated using heart rate. After that, cut-off points were determined in Matlab by using the Classification and Regression Trees (CART) method. The agreement for the cut-off points between T1 and T2 was analyzed.

Results MAD and MAI accelerometer values were lowest when children were lying on the floor and highest when running or doing jumping jacks. The mean correlation coefficient between acceleration values and heart rate was 0.595 ($p = 0.01$) for MAD metric and 0.611 ($p = 0.01$) for MAI metric, indicating strong correlations. Further, the MAD cut-off points for SB-LPA are 52.9 mg (hip), 62.4 mg (thigh), 86.4 mg (wrist) and 45.9 mg (chest), for LPA-MPA they are 173.3 mg (hip), 260.7 mg (thigh), 194.4 mg (wrist) and 155.7 mg (chest) and for MPA-VPA the cut-off points are 543.6 mg (hip), 674.5 mg (thigh), 623.4 mg (wrist) and 545.5 mg (chest). Test-retest comparison indicated good values (mean differences = 9.8%).

Conclusion This is the first study investigating cut-off points for children for four different sensor positions using raw accelerometer metrics (MAD/MAI). Sensitivity and specificity revealed good values for all positions. Nevertheless, depending on the sensor position, metric values differ according to the different involvement of the body in various activities. Thus, the sensor position should be carefully chosen depending on the research question of the study.

Keywords Children, Acceleration, Measurement, Activity, Sensor

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Background

The assessment of physical activity (PA) and sedentary behavior (SB) in children has gained more and more attention in recent years, as obesity and other health risks are increasingly occurring in childhood [1]. As regular PA is beneficial for the health status [2–6] as well as social and cognitive development in children [7], valid, reliable and feasible measurement options are essential for research examining activity behavior [8]. Activity monitoring typically is divided into two categories: subjective and objective measurement methods [9–13]. Valid subjective measures like surveys, activity diaries or interviews are inexpensive and therefore they are often used to assess PA behaviors in large groups of individuals [14]. Nevertheless, they often have low accuracy and depend on children's or their parents' recall bias [15–17].

In contrast, technical measurement methods, such as calorimetry, doubly labeled water, pedometers and accelerometry [9, 18, 19], allow for an objective and non-invasive assessment of PA, place less burden on study participants, and are of particular importance for younger children who show difficulties to recall or estimate their past PA, and whose intermittent activity patterns make proxy reports very difficult [20, 21].

Far less expensive and complicated than calorimetry and double labeled water are accelerometers and pedometers [8]. In addition, they eliminate recall bias and social desirability [22, 23]. These methods are commonly used for objective assessment of PA [14, 24]. Pedometers typically contain a mechanical sensor that, when moving up and down, records that movement as a step [24–27]. In contrast to pedometers, accelerometers can measure movement acceleration in multiple planes. This makes it possible to quantify the intensity, frequency and duration of an activity and not just the number of steps taken [13, 28–31]. Furthermore, accelerometers can be worn on different body positions such as hip, wrist, chest or thigh. The common use are hip worn accelerometers, that reveal accurate classification of activity type and correct classification of PA intensities [32, 33]. Nevertheless, there are advantages of wearing accelerometers on other body locations such as improved comfort [33]. In addition, measurement accuracy and compliance has consistently improved during the last years [33–35]. In particular, wrist accelerometers were more often used in recent studies as it has been shown to reach superior compliance in children compared to hip placement [36]. Additionally, studies with accelerometers worn on the wrist or thigh revealed that they detected more specific activities and yielded acceptably accurate assessment of energy expenditure and SB [33, 37, 38]. Due to its advantages, accelerometers are commonly used to quantify PA in adults, adolescents, and children.

For any given accelerometer, thresholds need to be developed using a calibration and validation study. So far, there exist various calibration studies concerning different age groups in children and adolescents like toddlers, elementary school children and adolescents by implementing various approaches [21, 22, 39, 40]. Nevertheless, current accelerometer studies used different accelerometers. Furthermore, these studies mostly used regression models to compute the energy expenditure from the captured raw data [41, 42]. However, to predict regression models, a reference method like indirect calorimetry is necessary. Nevertheless, this method is quite expensive as well as time-consuming. Further, calorimetry is a laboratory-study and is not useful in free living conditions and practicable for children [20, 43, 44].

The accelerometer Move4 (movisens GmbH) used in the present study has already been extensively validated and tested for adults in this way [45, 46]. Nevertheless, children's PA patterns and the resulting energy expenditure differ from adults and thus, separate cut-off points for PA intensities are need. Further, two different metrics exist that give the best possible indication of the intensity of physical movements and determine cut-off points for them for classification into activity levels. Thus, the research question of the present study is the calibration of the Move4 accelerometer for children aged 8–13 years. Specifically, we defined the following three aims:

Objective 1: Validation of the selected activities for the activity levels by using heart rate.

Objective 2: Modelling and determination of cut-off points to distinguish different activity levels (SB, light PA (LPA), moderate PA (MPA), vigorous PA (VPA)).

a. by using different metrics (see study description): mean amplitude deviation (MAD) [47] and movement acceleration intensity (MAI) [48].
b. by differing between the four sensor positions for mapping individual movement activities representation of cut-off points per movement activity per position.

Objective 3: Determination of the test-retest agreement by using data from two survey time points to determine the test-retest reliability of the Move4 together with the respective metrics.

Materials and methods

Study design

The longitudinal study is part of the EMPADIC (**E**xamination of **m**ethods for recording **p**hysical **a**ctivity and its **d**eterminants **i**n **c**hildren aged 8–13 years) – project. The study was approved by the local Ethics Committee (Ref. No. 56_20B) and was in accordance with the 1964 Declaration of Helsinki. All participants and their legal guardians provided written informed consent for the study participation. Data collection took place from May to September 2022.

Participants and procedure

For the present study, we included children aged 8–13 years. Recruitment took place in local sports clubs and schools in Bavaria (Germany). All participants were included if they were healthy and had no known diseases that restrict them from doing sport. In school, all children were excluded who are exempt from sports lessons due to health restrictions or who are unable to participate in physical education lessons. After written informed consent of the board of directors of the sports clubs and the school director, we contacted various divisions in the sports club as well as teachers and asked, whether they would like to participate in our study. Then, parents as well as children obtained an information document and both had to give written informed consent for study participation.

For data collection, we used a test-retest design, to assess the validity of the cut-off points and the agreement between cut-off points between T1 and T1. There was a timespan of one week between the two measurement points. Data collection was pseudonymous, so at the beginning each participant received a personal code consisting of a combination of letters and numbers. Furthermore, for each child, weight and height, which was measured by a stadiometer (seca 813 and seca 213, seca GmbH & Co. KG), as well as the age, were documented. The children's fitness status was recorded via the question "How many hours of exercise do you do per week?" (see Supplement 1).

For the calibration of the Move4 for children, participants performed nine different activities outdoors under the guidance of the trained research team like lying, sitting, standing, running with different pace, stairs climbing, catching, and throwing a ball as well as jumping jacks. These activities consider four intensity levels: SB, LPA, MPA, and VPA. Table 1 lists the performed activities and the expected MET values. Data collection took place in a 90-minute training session (60 min test, 30 min of preparation and follow-up). Before the start of the test, the children's verbal consent was obtained again. The sensors were applied to the children by the research team. For the present study, the children wore accelerometers at the following body positions: thigh (Move4); hip (Move4); wrist/ non-dominant hand (Move4) and chest (combination with ECG) (EcgMove4). When all sensors were properly attached, a jump was made to synchronize the sensors at each body position before the activities started. Such a jump was repeated after the activities have been performed. Subsequently, the children were instructed by the research team to perform each activity for a duration of four minutes. Average speeds for walking and running activities were estimated using defined distance and stopwatch. Further, a member of the research team guided the children through all activities and set the pace for the children for walking/running activities. This made it easier for the participants to maintain the estimated speed. During the implementation, the research team observed the participants and checked the correct performance of the activities. Between the four minutes activity there was a three-minute break to allow for transition between activities. After each activity

Table 1 Activity intensities, tasks and expected MET values

Activity intensity	Activity type (based on Evenson et al. [22] and Trost et al. [49])	Expected MET from Youth Compendium of Physical Activities [50]
Sedentary Behavior (1.0–1.5 MET)	Lying Lying supine on a floor mat with the arms at the sides. Instruction to minimize all physical movements	1.2
	Writing Sitting on a chair writing a text with the arms on the table	1.4
	Standing Standing with the possibility of small movements in the hip	1.7
Light Activity (1.5–2.9 MET)	Slow Walking (≈ 2 km/h)	2.6
Moderate Activity (3–6 MET)	Normal Walking (≈ 4 km/h)	3.5
	Throwing and Catching Throwing and catching a ball, with a distance of 3 m, about 15 throws per minute	4.1
	Stairs climbing Climbing stairs with 80 steps per minute	6.0
Vigorous Activity (> 6 MET)	Running (≈ 7 km/h) Alternative: running as fast as possible	7.4 8.5
	Jumping Jacks	7.1

children were instructed to stand still for 30 s to enable a separation of the activities. After completion of the nine activities the sensors were removed from the participants. Even if the rest between the activities was three minutes, we assume that the heart rate does not reach the resting heart rate after moderate and high intensity activities. As this could artefact the validation of the activities, we randomized the order of the activities for each data collection timepoint/study group.

Measurement instrument

The movisens sensor Move4 is a wearable device for measuring PA and sleep. The sensor EcgMove4 additionally records a single channel ECG and can be used to derive heart rate and heart rate variability. Both sensors have a 3-axis accelerometer and a 3-axis gyroscope for accurate detection of movements and body postures.

The sensor data is stored on an internal flash memory and can later be analyzed using the movisens Data Analyzer software [51, 52]. This software provides various analysis methods and visualization options to interpret the data and gain insights into PA, sleep and heart rate variability. Output parameters such as activity classes, body position, steps, energy expenditure and metabolic equivalents can be calculated.

The sensors are suited for use in scientific studies and interactive ambulatory assessment. They are used in a variety of applications, including sports performance analysis and rehabilitation [53–56].

The device is compact and lightweight, allowing for convenient and continuous use, and can be connected to a smartphone or other device for data transfer and analysis, e.g. to trigger questionnaires based on sensor data.

Data analysis

Descriptive statistics were calculated for study variables, mean (M) and standard deviations (SD) for continuous variables and frequency (%) for categorical variables. We conducted a test for normal distribution (Kolmogorov-Smirnov and Shapiro-Wilk) for all continuous variables. The data analysis of the accelerometer data was divided into two major steps: data preparation and data processing. During data preparation, Matlab version 2015b (TheMathWorks, Inc.) was first used to trim the sensor data to the measurements of each child. The sequence of activities was then read in so that the individual activities and the breaks in between could be marked in the sensor data. This reference annotation was used to assign the calculated PA values to the respective activity.

If there was an error in data acquisition for example an interruption of the activities during the measurement, for example because a child had to go to the toilet, a note was added accordingly. In line with the annotations, these sections were marked in the respective measurement and excluded from further processing. Relevant parameters were also added for further processing. These included gender, age, heart rate and the measurement time point in order to better compare the two time points. The data was processed using Matlab (TheMathWorks, Inc.) and the movisens software [51, 52]. Thereby, the PA metric values for the MAD [47] and MAI (based on Van Someren et al. [48]) metrics were determined using the movisens DataAnalyzer algorithms. For MAI, the acceleration signal was bandpass filtered (Butterworth 0.25-11 Hz, 4th order) to remove parts that are not caused by bodily movement. The three axes were fused by the Euclidean norm. The final signal output was the mean value of the output interval. Movisens uses an output interval of one minute [57]. In the literature, the MAD metric is also called Vector Magnitude Count (VMC) and makes use of the mean signal value to reduce the effect of the constant gravitational acceleration [58].

To confirm the validity of pattern-based classification of intensity, Pearson correlation coefficients were calculated between the heart rates and MAD/MAI acceleration values. In addition, Matlab was used to create boxplots representing the heart rates across activities.

Subsequently, these metric values were used to determine the cut-off points for the four different activity levels in Matlab by a decision tree using the Classification and Regression Trees (CART) method [59]. This method is based on the recursive partitioning technique and creates decision trees by recursively partitioning the data until a predefined stopping criterion (maximum depth) is reached. The goal of the CART method is to minimize the variance in the data while maximizing the information in the data.

We determined the cut-off points for the different intensity levels for each sensor position and for both measurement time points. Finally, we analyzed the sensitivity and specificity of our analysis by using one minute of each activity as a reference value.

Results

Socio-demographics

In the study participated 53 children (52% boys, 48%girls) aged 8–13 years (mean age=10.69±1.46). Overall, participants had a mean Body Mass Index (BMI) of 17.93 kg*m^{-2} (SD=2.89) ranging around the 60th percentile [60] and regularly engaged in sports for 61.26 (±26.16) minutes per day indicating overall a good fitness-level of the children. However, as seen in the standard deviation, children varied in their amount of sports activity per day. Test of distribution of the variables indicated a normal distribution of height, all other variables (age, weight, weight status, and sports activity) were not normal distributed. Further details can be seen in Table 2.

Table 2 Sample characteristics

	Overall	Boys	Girls
N (%)	53	28 (52%)	25 (48%)
Age [years; M ± SD]	10.69 (1.46)	10.73 (1.46)	10.66 (1.45)
Weight [kg]	38.92 (10.56)	39.13 (10.57)	38.78 (10.61)
Height [cm]	146.2 (11.40)	146.5 (11.27)	145.7 (11.10)
Body Mass Index (BMI) [kg*m^{-2}] (Range)	17.93 (2.89) 14.0–26.4	17.85 (2.97) 14.0–26.4	18.04 (2.80) 14.3–24.7
BMI percentile [60]		57.9th	61.8th
Sports activity [min/day] (Range)	61.26 (26.16) 21.4–128.6	69.16 (32.79) 21.4–128.6	52.86 (11.97) 34.3–85.7

Table 3 MAD and MAI metrics accelerations (mean absolute deviation, mg) in the nine activities. The lower part of the table presents the cut-off points from SB to LPA (Cut 1), from LPA to MPA (Cut 2) and from MPA to VPA (Cut 3)

	Hip		Thigh		Chest		Wrist	
	MAD	MAI	MAD	MAI	MAD	MAI	MAD	MAI
Activity	***Mean (SD)***	***Mean (SD)***	***Mean (SD)***	***Mean (SD)***	***Mean (SD)***	***Mean (SD)***	***Mean (SD)***	***Mean (SD)***
Lying	8.4 (5.2)	18.5 (15.5)	28.7 (46.3)	75.2 (123.5)	4.6 (5.5)	14.2 (15.3)	12.1 (19.1)	41.9 (55.6)
Sitting	10.9 (8.3)	37.2 (20.4)	55.0 (14.5)	155 (57.9)	5.9 (7.3)	24.6 (16.5)	28.2 (18.9)	84.5 (56.1)
Standing	26.6 (70.1)	49.3 (89.3)	25.4 (18.6)	90.9 (64.1)	23.9 (73.6)	45 (106.6)	38.6 (83.6)	86 (133.7)
Slow Walking	106.5 (33.6)	184.8 (42.8)	136.0 (6.9)	299.1 (32.9)	121.5 (39.5)	216.4 (49.5)	160.8 (61.6)	300.8 (102.4)
Normal Walking	215.9 (46.5)	306.9 (53.7)	209.9 (16.6)	394.5 (39.6)	243.2 (43.5)	357.7 (51.6)	248.0 (62.9)	402.7 (109.7)
Throwing and Catching	171.5 (67.4)	332.8 (95.3)	734.6 (24.6)	1159.5 (22.1)	162.5 (73.1)	294.1 (101.3)	549.3 (128.4)	929.7 (179.6)
Stairs Climbing	329.0 (94.6)	431.9 (115.2)	480.8 (57.1)	763.5 (84.1)	334.3 (98.7)	460.5 (123.1)	389.1 (128.5)	590.6 (198.1)
Running	832.7 (107.3)	1045.1 (135.1)	720.4 (28.7)	1364.3 (79.4)	763.2 (110.5)	1032.1 (139.5)	892.6 (139.4)	1599 (271.3)
Jumping Jacks	922.0 (135.4)	1070.2 (110.3)	725.9 (63.7)	1236.8 (65.2)	881.9 (98.3)	1023.9 (110.3)	975.8 (143.3)	1753 (193.1)

Mean values of each activity

Table 3 shows the accelerometer values for each activity broken down for MAI and MAD metrics. Overall, MAI values were higher than MAD. Mean accelerometer values were lowest when children were lying on the floor and highest when running or doing jumping jacks with no differences between boys and girls. The accelerations in each metric increase from intensity level to intensity level with the highest values for VPA.

Criterion Validity

Based on the individual mean values of each activity (MAD and MAI in mg), the criterion validity was then measured by correlation between the values of the MAD/MAI metric for each activity and the heart frequency (Ecg Move4). Overall, we had no limit of heart rate and thus no termination criteria. The mean heart rate for the SB activities was 105 beats (SD=23) per minute (bpm), 115 bpm (SD=18) for LPA, 132 bpm (SD=20) for MPA and highest value for VPA with 152 bpm (SD=21). The mean correlation coefficient between acceleration values and heart rate was 0.595 (p=0.01) for MAD metric and 0.611 (p=0.01) for MAI metric and thus, indicated a strong correlation between these the variables [61]. Figure 1 presents each activity with the associated heart rate.

Cut-off points of intensity levels/thresholds

The nine activities considered four intensity levels (see Table 4) and validity showed a strong correlation between activities and heart rate and thus, cut-off points for SB-LPA, LPA-MPA as well as MPA-VPA could be determined. Table 4 shows the three cut-off points for the MAD and MAI metric for all four sensor positions. Overall, there were no meaningful differences in the cut-off points between boys and girls. Thus, we mention the overall cut-off points.

Overall, cut-off points differ between the two metrics with higher values for MAI across all sensor positions (see Table 4). In particular, the MAD values of the hip sensor are for SED (0-52.9 mg), LPA (53-173.3 mg), MPA (173.4-543.6 mg), VPA (>543.6 mg).

Sensitivity and specificity

Sensitivity and specificity for classification of each PA intensity category within the MAD metrics are displayed in Table 5. For SB, the wrist worn accelerometer had highest sensitivity (98.9%), but the hip worn has highest specificity (99.1%). For LPA, MPA and VPA, sensitivity (92.0%) as well as specificity (70.8%) were highest for the chest worn accelerometer. Overall, the chest position indicated the highest sensitivity (91.1%) and specificity (82.1%) values across all intensity levels for the MAD metrics.

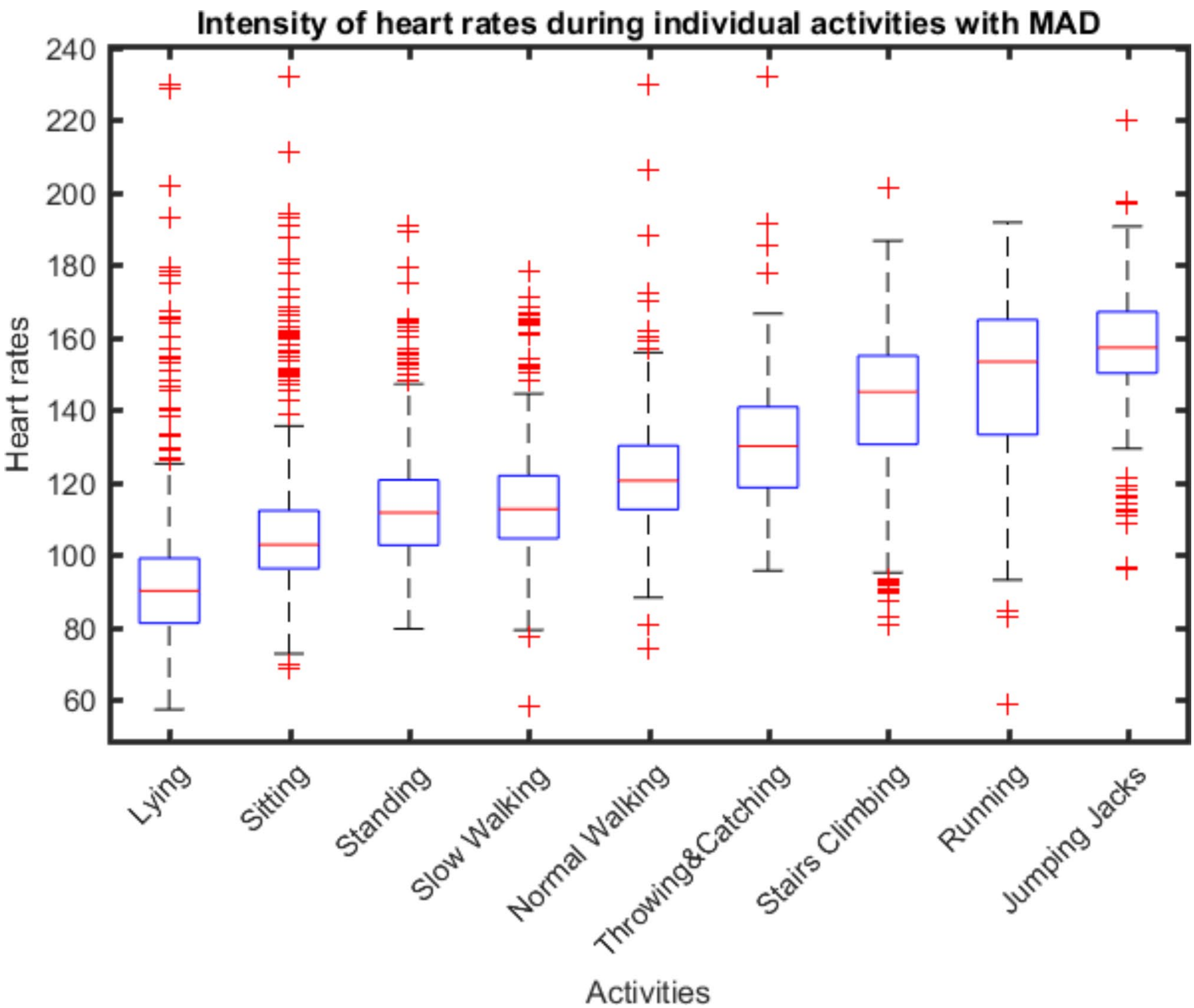

Fig. 1 Intensity of heart rates during individual activities

Table 4 Overall cut-off points with MAD and MAI metrics (mg)

	Cut 1 (SB-LPA)		Cut 2 (LPA-MPA)		Cut 3 (MPA-VPA)	
Accelerometer	***MAD***	***MAI***	***MAD***	***MAI***	***MAD***	***MAI***
Hip	52.9	121.9	173.3	285.6	543.6	723.2
Thigh	62.4	182.5	260.7	457.7	674.5	858.3
Wrist	86.4	183.8	194.4	337.4	623.4	1058.9
Chest	45.9	101.5	155.7	240.2	545.5	672.8

Table 5 Sensitivity and Specificity of cut-off points (MAD metrics)

	SB		LPA		MPA		VPA		Overall	
Accelerometer	***Sens. (%)***	***Spec. (%)***	***Sens. (%)***	***Spec. (%)***	***Sens. (%)***	***Spec. (%)***	***Sens. (%)***	***Spec. (%)***	***Sens. (%)***	***Spec. (%)***
Hip	97.4	99.1	89.5	70.3	71.4	60.1	99.1	96.6	89.3	81.5
Thigh	98.3	98.9	87.8	66.9	44.8	59.5	91.9	99.0	80.7	81.1
Wrist	98.9	97.5	77.3	68.7	67.7	60.0	97.1	99.0	85.2	81.3
Chest	96.7	99.4	92.0	70.8	76.2	60.0	99.3	98.3	91.1	82.1

Table 6 Sensitivity and Specificity of cut-off points (MAI metrics)

	SB		LPA		MPA		VPA		Overall	
Accelerometer	***Sens. (%)***	***Spec. (%)***	***Sens. (%)***	***Spec. (%)***	***Sens. (%)***	***Spec. (%)***	***Sens. (%)***	***Spec. (%)***	***Sens. (%)***	***Spec. (%)***
Hip	95.8	99.5	91.4	70.7	69.0	60.1	99.2	94.4	88.8	81.2
Thigh	98.2	98.3	93.0	66.1	32.2	59.8	95.7	96.4	79.7	80.1
Wrist	97.9	97.9	65.3	68.4	61.2	47.3	75.8	98.5	75.1	78.0
Chest	81.6	99.7	89.6	73.6	76.8	60.1	99.5	93.4	86.9	81.7

Table 7 Differences between T1 and T2 valued for the MAD and MAI metric (mg)

	Cut 1 (SED-LPA)			Cut 2 (LPA-MPA)			Cut 3 (MPA-VPA)			Overall
Accelerometer	**T1**	**T2**	**Difference**	**T1**	**T2**	**Difference**	**T1**	**T2**	**Difference**	**Difference**
MAD METRIC										
Hip	49.0	52.9	-8.0%	183.4	158.2	15.0%	549.1	542.0	1.0%	8.0%
Thigh	55.9	53.0	5.0%	283.7	247.0	14.0%	687.1	643.4	7.0%	8.7%
Chest	49.5	42.7	15.0%	157.6	155.4	1.0%	564.3	545.5	3.0%	6.4%
Wrist	94.4	76.3	21.0%	205.9	164.9	22.0%	623.4	664.5	-6.0%	16.3%
Overall			12.3%			13.0%			4.3%	
MAI METRIC										
Hip	130.5	115.1	13.0%	286.0	273.7	4.0%	760.5	723.2	5.0%	7.3%
Thigh	198.4	178.3	11.0%	484.5	457.2	6.0%	855.2	907.7	-6.0%	7.6%
Chest	100.3	109.5	-9.0%	237.8	223.3	6.0%	689.1	672.8	2.0%	5.6%
Wrist	180.4	211.5	-16.0%	337.4	385.1	-13.0%	1072.5	938.3	13.0%	14.0%
Overall			12.3%			7.3%			6.5%	

Sensitivity and specificity for classification of each PA intensity category within the MAI metrics are displayed in Table 6. For SB, the thigh worn accelerometer had highest sensitivity (98.2%), whereas specificity (99.7%) was highest for the chest worn accelerometer. For LPA, the thigh position indicated the highest sensitivity (93.9%) but the chest worn the highest specificity (73.6%). For MPA, sensitivity (76.8%) as well as specificity (60.1%) were highest for the chest worn accelerometer. Sensitivity (99.5%) for VPA was highest at the chest position and specificity (98.5%) at the wrist position. Overall, the hip position indicated the highest sensitivity (88.8%) and the chest position the highest specificity (81.7%) values across all intensity levels for the MAI metrics.

Test-retest agreement

As our study had a test-retest design, we compared the determined cut-off points for the intensity levels for all accelerometer positions between T1 and T2. Overall, for the MAD metric, the mean difference between T1 and T2 was 9.85% with greatest differences for the wrist worn accelerometer (16.3%) and lowest difference for the chest worn (6.4%). Independently of the accelerometer position, the highest deviation was seen for the SB-LPA cut and the LPA-MPA cut (see Table 7).

Similar results can be seen for the MAI metrics (see Table 7). Overall, the mean value of deviation between T1 and T2 was 8.63% with greatest differences for the wrist worn accelerometer (14.0%) and lowest difference for the chest worn (5.6%). Independently of the accelerometer position, the highest deviation was seen for the SB-LPA cut and the cut-off points for LPA-MPA and MPA-VPA had equal differences across all positions.

Discussion

The aim of the present study was the calibration of the Move4 accelerometer for children aged 8–13 years. In more detail, firstly mean values for the selected activities (in mg for MAD and MAI metric) were assessed and then these activities and the energy expenditure were validated by using the heart rate. Secondly, cut-off points were modelled and determined to distinguish different intensity levels by using two different metrics (MAD and MAI) as well as by differentiating between the four sensor positions.

Validity

First of all, the determination of activities and energy expenditure level was validated by using the heart rate measures. Overall, a strong correlation between the heart rate and the MAD values (in mg) of each activity was found. With increasing MET values, the heart rate of the activities increased. Based on this finding, it is possible to determine the cut-off points by using the MAD/MAI values of the activities. The present results are consistent with previous reports stating that heart rate is effective in detecting a variety of activity patterns [40]. Nevertheless, as we randomized the order of the activities, it was possible, that in some groups SB activities followed right after VPA activities. In that case, the three minutes rest could not have been enough time to normalize the heart rate. This could explain slightly higher heart rates of 105 bpm for SB compared to physiological studies indicating a resting heart rate of 90–95 bpm in this age range [62, 63]. In this context, it is worth mentioning that the validation of the activities was based on children with an overall good fitness level (mean activity minutes per day=61.2) and a normal weight (overall BMI=17.9 kg/m^{-2}, 60th percentile). Nevertheless, there were differences in the amount of activity and weight status between the children (see Table 2), resulting in differences in the HR while performing the activities [64]. This needs to be considered when interpreting the data. Still, as the mean value is quite good, we assume that the determined cut-off points can be used for children with a normal weight status and fitness level.

Selection of activities

In this context, the selection of the activities for the present calibration study should be discussed. First of all, a combination of locomotor activities (e.g., slow walking with 2 km/h) and other free-play activities (e.g., throwing and catching a ball) was used to better simulate the different types of activities that children engage in. These were common to children of this age group and provided both, varying intensity levels and ranges of accelerometer counts [22]. This is also a principle suggested by Welk [65] and was used in several studies so far [66–69]. Furthermore, nine activities were used which is also applied in other studies [40, 41, 65, 68, 70]. The selection and classification of the used activities is based on the Youth Compendium of Physical Activity [50]. Unfortunately, only one activity (slow walking) was selected for LPA. Thus, it is suggested that further studies should apply an equal number of activities for each of the four PA intensity levels.

Cut-off points

There is a need for using raw acceleration data instead of activity counts for measuring the intensity of PA [71–73]. Thus, the present study compared two different raw acceleration metrics (MAD and MAI) for the calibration of the Move4 sensor across four sensor positions in children aged 8–13 years. Within the discussion, further focus will set on the results of the MAD metrics, because, to the best of our knowledge, there is no validation and calibration study using the MAI metric so far. Nevertheless, this metric is also important as it uses a bandpass filter that ensures that accelerations that do not come from physical movements tend to be filtered out and is more and more used in studies [74, 75], so it was decided to determine the cut-off points for both MAD and MAI metrics. In comparison to Aittasalo et al. [70] who used the MAD metric for a hip worn accelerometer in children aged 13–15 years, our cut-off points differ especially in Cut 1 (SB-LPA: 52.9 vs. 26.9 mg;) and Cut 2 (LPA-MPA: 173.3 vs. 332 mg). One reason for the difference in the lower values in our study for LPA-MPA cut-off points might be the allocation of the activities to the intensities: In the present study, slow walking was the only activity for LPA and normal walking for MPA (oriented to the Youth Compendium of Physical Activity [50]), whereas Aittasalo et al. [70] allocated slow walking as well as normal walking to LPA. Another study using the MAD metric in 11 year old children indicated as the optimal cut-off points for LPA-MPA (=3 MET) 91 mg and the MPA-VPA (=6 MET) cut-off points was at 414 mg [47]. However, in this study participants performed a pace-conducted non-stop test on a 200 m long oval indoor track with initial speed of 0.6 m/s and it was increased by 0.4 m/s at every 2.5 min [47]. As free-living activities were also included, this could be the reason for the differences in the cut-off point from LPA to MPA (173.3 vs. 91 mg). In summary, our data show that the values respectively the cut-off points differ between the studies. This could be due to different samples, different activities and therefore it is important that for each sensor cut-off points are formed to make them usable for studies.

Sensor positions

To the best of our knowledge, this was the first study comparing four sensor positions of any accelerometer. Existing studies compared in particular hip and wrist worn accelerometer [41] or hip, wrist and thigh [68], but none compared the hip, thigh, wrist and chest position for sensor location. As the different body positions are involved differently in the nine activities, it is not surprisingly that the cut-off points differ slightly across the four sensor positions.

Regarding sensitivity and specificity of each sensor position, our results indicated overall for the hip as well as for the thigh the highest specificity (MAD hip: 88.8%; MAD chest: 82.1%) as well as sensitivity (MAD hip: 89.3%; MAD chest: 91.1%) whereas the sensitivity and specificity for the wrist indicated in MAD metrics 85.2% respectively 81.3%. In contrast, Johansson et al. [41] indicated for wrist and hip worn sensors same sensitivity (SB: 100%, MVPA: 70%) and specificity (SB: 60%, MVPA: 100%) values in preschool children. Sensitivity and specificity values for two hip worn accelerometers indicated in children aged 13–15 years almost perfect values for all cut-off values (98.6-100%) [70]. The different values of sensitivity and specificity in various studies could be explained by the selection of the activities. Depending on how far the MET values of the activities are from the MET-cutpoint (e.g., 3 MET), there are different metric cut-off points and different accuracies in the detection. In comparison, a study investigating adults found high accuracy of the thigh-worn accelerometer for predicting time spent in each PA intensity category, as seen by sensitivities and specificities > 99% for correctly classifying each PA intensity category [68]. One possible explanation for the differences between children and adults could be the inconsistent performance of activities in children whereas adults could more consequently perform activities over a certain time period [76].

Furthermore, regarding the accelerometer output (in mg) within one intensity level, there are differences according to the body position to which the sensor is attached. In particular, the MAD metrics for SB varied widely in our study: 52.9 mg for the hip placement, 62.4 mg for thigh, 86.4 mg for the wrist sensor and 45.9 mg for the chest position. The high values of wrist worn accelerometers in SB could be explained by the fact that this sensor position captures movements performed by the arms, unlike a hip worn monitor [41]. Especially younger children have problems to stand still without moving their arms [41]. Our findings are in accordance with results from other studies [36, 41, 77] which showed higher values for wrist-worn accelerometer compared with hip worn sensors, while measuring simultaneously.

Recommendations for sensor positions

We suggest to choose the sensor position depending on the research question. Overall, the sensor at the hip is really comfortable and shows good values and is already commonly used [32, 33, 78, 79]. Furthermore, the hip worn sensor indicated good sensitivity and specificity values in our study. Nevertheless other body positions should be considered while planning a study [68]. In particular, accelerometers worn on the thigh have shown high accuracy for measuring several different PA levels as well as SB and sleep [33, 38, 80–84]. Further, if there is an interest in the heart rate of the participants, the EcgMove4 accelerometer worn at the chest is suggested. Thus, it is easy to assess time spent in different intensity levels as well as the heart rate. The least favorable and efficient position seems to be the wrist due to low sensitivity and specificity.

Test-retest agreement

Lastly, to assess the accuracy of the Move4 sensor, a test-retest design for the agreement of the cut-off points between T1 and T2 for all sensor positions was used. Overall, agreement indicated good values with small differences between T1 and T2. Regarding the cuts, Cut 1 and 2 indicated higher deviations compared to Cut 3. This could be explained by the types of activities within one PA level allowing greater variations in the execution. Especially during the SB activities (standing and lying), some children problems to hold the position and not to move their bodies, especially their arms. In contrast, VPA activities required the whole body to move which allows less variations in execution.

Regarding the sensor positions, only the wrist worn accelerometer showed great differences especially for SB-LPA and LPA-MPA cut-off points. A problem is that the wrist worn accelerometer output is highly depending on the movements of the hands [41]. In particular, the task standing for four minutes was highly challenging for some children and variances were recognized between the children (inter-individual) and also between the two measurement points (intra-individual) in relation to the movement of the hands. This could explain the differences of 16.3% between T1 and T2 cut-off points.

Strengths and limitations

The main strength of our study is our sample size of 53 children aged 8–13 years which was numerous compared to other studies investigating between 20 and 47 participants [21, 41, 47, 70]. Furthermore, we calibrated and tested the Move4 sensor at four different body positions (hip, thigh, non-dominant wrist, and chest). Thus, the validation of the sensors was successful regarding a wide range of application possibilities. In addition, the different activities were not selected randomly, rather following the Youth Compendium of Physical Activity. Butte et al. [50] developed various activities and their resulting energy consumption in MET values. This is a meaningful list of activities and is a valuable resource. Furthermore, to ensure that the activities are performed with high accuracy, one research assistant was leading and participating in the exercise. This was highly important for the walking and running activities to lead the pace.

A limitation of this study relates to different weather conditions during the time period of the data collection. Therefore, some of the exercises were carried out indoors, which may have affected the children's movement. Secondly, the sensors have partially fallen off during the movements. Although they were immediately reattached, a few seconds of activity had to be cut out. Further, some participants had difficulties to perform the activity the whole duration of four minutes. Thus, the data preparation contains cut outs to clean the raw data. Besides performing for four minutes, the accuracy of the execution lacked (e.g., standing). In this context, the validation of the activities and thus the determination of the cut-off points need to be slightly limited as the sample differed within the amount of activity (fitness level) and weight status, which might result in variability of the heart rate within one activity. Lastly, we only had one activity for the LPA intensity level that could be not representative for this level. Nevertheless, our data show good validity of the activities and the MET values. Further studies should consider that all intensity levels include more than one activity.

Conclusion

This is the first calibration study using two different metrics (MAD/MAI) based on raw accelerometer data as well as determining cut-off points for four sensor positions using movisens Move4 sensor. Overall, our validation of the activities in regard to MET values by heart rate shows good correlation. Thus, the cut-off points showed good values for sensitivity and specificity. Test-retest agreement indicated good values with slightly more deviation from T1 to T2 in the wrist worn accelerometer. The optimal sensor position should be chosen depending on the research question of the study. Further calibration studies are needed for younger children, especially preschool children, as their activity patterns differ from children included in our study.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13102-023-00775-4.

Supplementary Material 1

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Authors' contributions

Conceptualization: F.B., I.M., A.K.R.; Methodology: F.B., I.M., A.K.R.; Formal analysis and investigation: A.E., F.B.; Writing – original draft preparation: F.B.; Writing – review and editing: F.B., I.M., A.E., S.S., C.T. A.K.R.; Supervision: A.K.R.

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Data availability

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

Declarations

Ethics approval

The study was approved by the local Ethics Committee of the Friedrich-Alexander-Universität Erlangen-Nürnberg (Ref. No. 56_20B) and was in accordance with the 1964 Declaration of Helsinki.

Consent for publication

Not applicable.

Consent to participate

Informed consent from all participants and their legal guardians for the study participation.

Competing interests

Alina Eisenreich is an employee of the moviens GmbH. Movisens provided the sensors. All other authors declare no competing interests.

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Publisher's Note

Summary

This was the first calibration study using two different metrics (MAD/MAI) based on raw accelerometer data as well as determining cut-off points for four sensor positions using Movisens Move4 sensor. Overall, our validation of the activities regarding MET values by heart rate showed strong correlation. Further, the calculated and determined cut-off points showed good values for sensitivity and specificity. Test-retest agreement indicated high percentages with slightly more deviation from T1 to T2 in the wrist worn accelerometer. The optimal sensor position should be chosen depending on the research question of the study. Further calibration studies are needed for younger children, especially preschool children, as their activity patterns differ from children included in our study.

Consequences

The previous chapter highlighted the advantages of device-based measurement methods (including a calibration of an accelerometer for children aged 8-13 years), especially for assessing physiological variables of PA. Due to the quantifiability and the high accuracy of PA levels when using device-based methods (Reilly et al., 2008), activity compensation in children and adolescents will firstly be investigated by focusing on a device-based approach. Within the following chapters (4.1.2 and 4.1.3), focus should lie on activity compensation by using device-based measurement methods.

4.1.2 Manuscript C: Compensation or Displacement of Physical Activity in Children and Adolescents: A Systematic Review of Empirical Studies

Beck, F., Engel, F. A., & Reimers, A. K. (2022). Compensation or Displacement of Physical Activity in Children and Adolescents: A Systematic Review of Empirical Studies. *Children*, *9*(3). https://doi.org/10.3390/children9030351

Introduction

Activity compensation has been identified as a potential explanation for insufficient and mixed intervention effects (Rowland, 1998). Nevertheless, activity compensation is not yet well understood. Overall, there is a debate concerning whether activity compensation occurs (Reilly, 2011; Wilkin, 2011) and further, little is known about how compensation may occur, to whom it may occur, and any reasons for its occurrence. For the first step, we conducted a systematic review to get an overview of compensatory behavior in children and adolescents. By including only studies with a device-based approach, compensatory mechanisms were analyzed across different categories, which seemed to be helpful for understanding compensation. In this respect, the aim was to determine which study design, target group, measurement instrument, PA context, timespan, and intervention duration, as well as type, was susceptible to compensation.

children MDPI

Review

Compensation or Displacement of Physical Activity in Children and Adolescents: A Systematic Review of Empirical Studies

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Abstract: Regular physical activity during childhood and adolescence is associated with health benefits. Consequently, numerous health promotion programs for children and adolescents emphasize the enhancement of physical activity. However, the ActivityStat hypothesis states that increases in physical activity in one domain are compensated for by decreasing physical activity in another domain. Currently, little is known about how physical activity varies in children and adolescents within intervals of one day or multiple days. This systematic review provides an overview of studies that analyzed changes in (overall) physical activity, which were assessed with objective measurements, or compensatory mechanisms caused by increases or decreases in physical activity in a specific domain in children and adolescents. A systematic search of electronic databases (PubMed, Scopus, Web of Science, SportDiscus) was performed with a priori defined inclusion criteria. Two independent researchers screened the literature and identified and rated the methodological quality of the studies. A total of 77 peer-reviewed articles were included that analyzed changes in overall physical activity with multiple methodological approaches resulting in compensation or displacement. Of 40,829 participants, 16,265 indicated compensation associated with physical activity. Subgroup analyses separated by study design, participants, measurement instrument, physical activity context, and intervention duration also showed mixed results toward an indication of compensation. Quality assessment of the included studies revealed that they were of high quality (mean = 0.866). This review provides inconclusive results about compensation in relation to physical activity. A trend toward increased compensation in interventional studies and in interventions of longer duration have been observed.

Keywords: compensation; displacement; physical activity; children; adolescents

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1. Introduction

1.1. Health Benefits of Physical Activity

Regular physical activity (PA) during childhood and adolescence is associated with numerous health benefits [1]. As a result of regular PA, physical fitness in children increases, and is associated with improvements in cardiovascular [2] and cardiometabolic [1,2] health, as well as with a reduction in obesity risk [3–5]. Additionally, PA is associated with better mental health in children and adolescents [6,7].

In line with these findings, the World Health Organization (WHO) [8,9] developed PA recommendations for children and adolescents. Briefly, it is recommended for children 5 to 17 years of age to accumulate at least 60 min of moderate-to-vigorous PA (MVPA) daily [9]. However, recent analyses have demonstrated that PA levels of children and adolescents in many regions worldwide are not meeting the WHO recommendations [10–12].

1.2. ActivityStat Hypothesis and Compensatory Mechanisms

PA promotion serves as a preventive health strategy [13,14], and there are numerous efforts to promote PA in children and adolescents to develop more active lifestyles [15–18]. To succeed with the health benefits of PA, it is essential to fully understand the PA determinants. Most research thus far has focused on the psychosociological, social, and environmental issues that affect PA levels [19]. In contrast, the potential effect of intrinsic biological control on regular activity has received little attention [20].

With Rowland's "ActivityStat" hypothesis [21], the research on biological control that underpins PA and energy expenditure has gained momentum in the literature [22]. Briefly, the ActivityStat hypothesis suggests that an imposed increase or decrease in PA in one domain might induce a compensatory change in the opposite direction in another domain in order to maintain a level of PA or energy expenditure that is overall stable over time [22]. Thus, based on the ActivityStat concept, human beings maintain their total PA at a constant level by adapting various mechanisms, such as increasing or decreasing the frequency, intensity, or duration of time spent engaged in PA [23]. By such adapting mechanisms, their actual energy expenditure can either be increased or decreased so that the overall energy expenditure is stable over a certain period of time. For example, on a day when a child has physical education (PE) classes at school, the child may experience an increase in PA in the morning. However, the child may subsequently increase the time that they spend being sedentary in the afternoon, resulting in an overall PA level that is not increased for this day.

This compensatory mechanism has been observed in some interventional studies: school-based interventions [24–31] demonstrated small or moderate effects on increasing PA within the school setting, but little to no changes in terms of overall PA levels as a result of compensatory mechanisms employed outside of the school setting. Nevertheless, in order to obtain evidence regarding the general effectiveness of interventions on overall PA levels, a holistic approach is important—one that analyzes different domains and time periods of a day (e.g., physical activities in school and outside of school) in addition to overall PA. Such analyses could provide insights into the potential compensatory mechanisms and rearrangements mentioned in the ActivityStat hypothesis.

1.3. Displacement Hypothesis

The original displacement hypothesis postulates a mechanism that opposes the ActivityStat hypothesis, stating that watching television and other sedentary behaviors may displace PA [32]. Different studies have suggested that an increased amount of time spent being sedentary is the primary factor contributing to the current increase in obesity seen in adolescents [33–37]. Due to its inverse relationship, this original hypothesis can also be used to justify the displacement of inactivity with PA. However, little evidence exists that supports this assumption in children and adolescents under 18 years of age [38–40]. However, a Cochrane systematic review of school-based PA programs has concluded that there is solid evidence that school-based interventions have a positive impact on the duration of PA, with generally no effects on leisure time PA [16]. The review implies no substantial evidence that compensation is being made for PA imposed through interventions by having the PA decrease in another domain [16].

1.4. Previous Reviews Analyzing Compensatory Mechanisms in Children and Adolescents

Little is known about how PA varies in children and adolescents within intervals of one and multiple days [22,41]. Additionally, the question arises as to whether and how inactive or sedentary time can be displaced by PA within one day or over a period of several days in children and adolescents. For children and adults, a systematic review by Gomersall, Rowlands, English, Maher, and Olds [22] found inconclusive results with regard to the ActivityStat hypothesis. This review was limited in its scope because it exclusively considered studies that made explicit reference to compensation. Additionally, in the previous review, both children and adults were assessed, and objective as well as subjective measurement methods were used. Overall, to the best of our knowledge, no review has yet analyzed PA compensation in children and adolescents only within intervals of one and multiple days with objective measurement methods.

1.5. Aims of the Present Review

Starting from this state of research, this systematic review aims to provide a synthesis of studies that analyzed changes in overall PA among children and adolescents within various contexts of PA. Specifically, the present review aims: (i) to provide an overview and analysis of studies that examined changes in (overall) PA, assessed with objective measurements, in children and adolescents; and (ii) to identify the displacement of PA or whether compensatory mechanisms following PA increase or decrease in one domain or during a timespan of the day (e.g., at school, in the morning) or in terms of the amount at a specific intensity level (e.g., light, moderate, or vigorous PA).

2. Methods

This systematic review was performed and is reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [42].

2.1. Eligibility Criteria

Studies were deemed to be eligible if they met the following inclusion criteria and were excluded for the review if one or more exclusion criteria applies (Table 1).

Table 1. Inclusion and exclusion criteria for the systematic review.

	Inclusion Criteria	Exclusion Criteria
Measurement method	Objectively measured PA or energy expenditure	Subjectively measured dependent or independent variables
Outcome	Investigation and analysis of changes in (overall) PA or (overall) energy expenditure caused by an increase in PA in a specific domain or during a specific timespan (e.g., at school; in the morning)	• Studies with only one measurement point; • Studies that do not report an overall PA or energy expenditure score.
Population	• Participants in the study were healthy; • Studies with children and adolescents (3 to 19 years of age, or their mean age was in this range) [43].	• Participants with chronic diseases; • Studies among participants with a competitive athletic background; • Participants under the age of 3 or older than 19 years.
Publication type	Studies published in a peer-reviewed journal in English or German	• Grey literature; • Publications without peer review; • Publication language other than German or English.
Publication date	Articles published in the year 2000 or later	Articles published before 2000

We decided to focus on objective measurement methods due to the advantages over subjective methods. These are limited to poorer reliability and validity, as well as participants recall bias [44]. Objective measurements are able to directly assess one or more dimensions of PA (intensity, frequency, time and type) and a variety of metrics such as step numbers, minutes or intensity [45].

We included interventional as well as non-interventional studies. Interventional studies offered the opportunity to obtain information about "ActivityStat" by investigating within-subject changes in PA levels in response to an intervention stimulus. Non-interventional studies were included if they investigated PA levels of individuals during different timespans or in different domains over a period of several days.

2.2. Search Strategy

The search was performed on 31 March 2020 using the electronic databases PubMed, Scopus, Web of Science, and SportDiscus. In contrast to Gomersall, Rowlands, English, Maher, and Olds [22], the search term in the present review was not limited to the term compensation: the search strategy included using a combination of terms related to children and youth (child* OR youth* OR adolescen* OR boy* OR girl* OR student* OR pupil*), terms related to PA compensation (increas* OR decreas* OR "more activ*" OR improve* OR "less activ*" OR compensat* OR displace* OR change* OR activitystat), terms related to measurement methods ("objective* measure*" OR acceleromet* OR pedomet* OR "heart rate monitor*" OR "doubly labeled water" OR calorimet* OR "direct* observ*"), and outcome-related terms ("physical activ*" OR "energy expenditure"). Two filters were used to refine the results and to obtain the final reference sample for screening. In accordance with the set inclusion criteria, studies published between 2000 and 2020 were selected. The publication type was filtered for journal articles (PubMed: "journal article"; SportDiscus: "academic journal", "peer reviewed"; Scopus: "articles"; Web of Science: "Article"). In accordance with recommendations for systematic reviews [46], we screened the reference lists and citations of included articles in order to identify additional relevant studies.

2.3. Study Selection

Identified references were imported into Endnote X9, a reference management software [47]. Subsequently, the citations were imported into Covidence, a systematic review software [48]. Within this program, all duplicates were removed. This step was followed by a three-step study selection process, comprising (1) title-screening, (2) abstract-screening, and (3) full-text-screening for inclusion criteria by two independent reviewers (F.B. and a trained student assistant). During each step of the screening process, all references that could not conclusively be excluded were kept for further screening in the next step. Disagreements between the two reviewers in relation to final inclusion were resolved through discussion with a third researcher (A.K.R.).

2.4. Data Extraction

The following data were extracted from each article: author(s); country; study design; sample description (number of participants, age, sex); aim/purpose of the study; measurement and instrument of measurement as well as duration of measurement; context of PA, main study results on the relationship between PA in one domain and PA in another domain/overall PA; and statistical indicators for compensation. In particular, this was referred to as the *p*-value for between- and within-group comparisons of PA or energy expenditure levels in one domain/timespan and the following domain/timespan (see also Electronic Supplementary Material File S1).

Studies were also classified by taking into consideration different settings or contexts in which PA was measured. In relation to the main objectives of the study, six settings were defined (school-based PA, physical education, active commuting to school, daily pattern, sport clubs, and others). All included studies were allocated to one of these categories.

2.5. Quality Assessment

The methodological quality of the included studies was rated by two independent reviewers (F.B. and a trained student assistant). To assess the quality of each study, criteria for evaluating primary research articles, developed by Kmet et al. [49], were applied. We decided to use this tool because it is appropriate for a variety of different study designs. The "QualSyst" scoring system is based on existing tools and particularly relies upon the instruments developed by Cho and Bero [50] and Timmer et al. [51] for quantitative studies. A series of 14 items was used to assess quality. These items included questions related to study design, methods of participant selection, random allocation procedure, blinding, outcome measures, sample size, estimate of variance, confounding, reporting of results, and the evidence base for the conclusion. The items were scored depending on the degree to which each criterion was met ("yes" = 2, "partial" = 1, "no" = 0). If an item was not applicable to a particular study design, it was coded with "N/A" and was excluded from the calculation of the summative score. Randomization was only scored in interventional studies. The following equation was applied for estimating quality scores: 28 − (number of N/A × 2). Consequently, 28 was the maximum score that could be obtained for the 14 questions. The risk of bias was evaluated with its summary score (range 0–1), whereas higher scores indicated better methodological quality.

2.6. Synthesis of Results

It was anticipated that the studies included in this systematic review would exhibit a diverse range of research methods (e.g., study design, intervention characteristics, setting, measurements, participant characteristics, and outcome measures). Therefore, it was not appropriate to use meta-analysis to integrate and summarize the included studies. Instead, a narrative synthesis of results was performed. Summary tables describing the detailed characteristics of included studies and the visualization of statistical indicators, describing the probability for compensation related to these characteristics, were provided. The included studies and their findings were grouped according to the study design, sample size, target group, dependent variable, geographic origin, PA context, measurement instrument, duration of intervention (if this information was provided), intervention type, and the timespan in which compensation was measured. Analyses of compensatory mechanisms were performed for different categories, which seemed to be helpful for understanding compensation. In this respect, the aim was to determine which study design, target group, measurement instrument, PA context, timespan, and intervention duration, as well as type, was susceptible to compensation. A study was voted to be "supporting compensation" if the overall PA did not change with respect to different time points, or if it did not differ between intervention group(s) and control group(s), or if there was a significant increase in PA in one domain or timespan and a significant decrease in PA in another domain or timespan.

3. Results

3.1. Flow Chart

A total of 5917 potentially relevant articles (or 10,946 including duplicates) were identified through database searches, and their titles and abstracts were screened. In the next step, the full texts of 95 studies were retrieved for in-depth screening. Since 20 articles were excluded due to inappropriate aims of study, statistical analysis, participants, or multiple reasons, a total of 75 articles were identified as eligible and were included in this systematic review. Subsequently, 2 additional relevant publications were identified through backward reference tracking, yielding a total of 77 articles reporting on 74 unique studies included in this systematic review (Figure 1). PA as a Civil Skill Program was published in two studies that focused on LPA [52] and moderate PA (MPA) [53], respectively. The PHASE-Study was also reported in two separate articles. Ridgers et al. [54] focused on the association between daily PA on two following days, whereas Ridgers et al. [55] analyzed the correlations between the amount of sitting, standing, and stepping time within and between days in primary schoolchildren. Furthermore, two articles included in this review were part of the TEACHOUT-Study and investigated general effects of education outside the classroom [56] and effects of education outside the classroom in different domains [57].

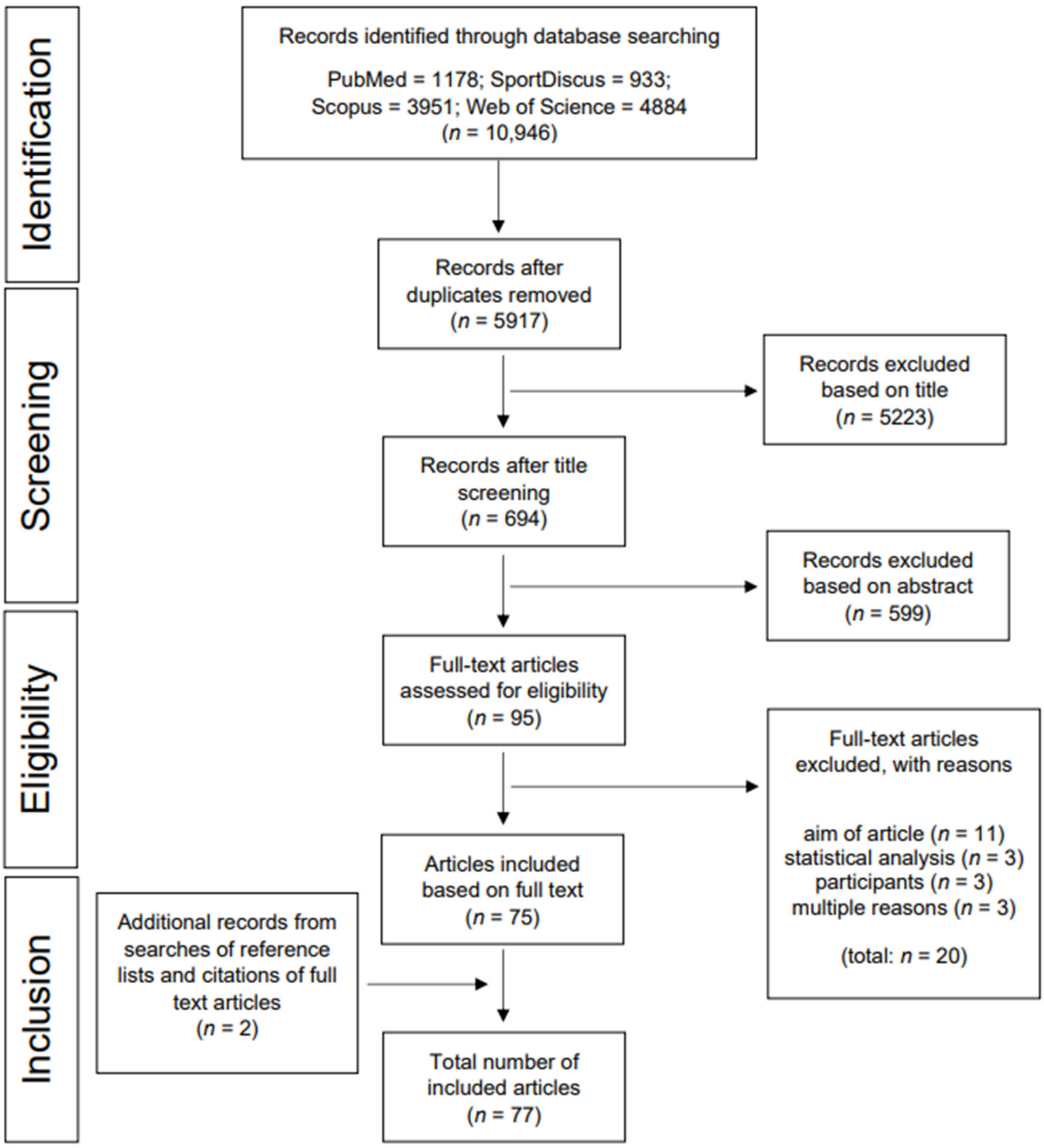

Figure 1. Flow chart.

3.2. Characteristics of Included Studies

A complete data extraction table for each included study can be found in Electronic Supplementary Material File S1. A synthesis of the characteristics of the included articles is presented in Table 2. The majority of included articles (n = 49; 64%) presented non-interventional studies and 36% presented interventional studies. The sample size ranged from 13 [58] to 6916 participants [23], with a mean sample size of 532 participants. The geographical origin of the studies was as follows: n = 40 Europe, n = 21 North/Mid America, n = 10 Australia/New Zealand, and n = 6 Asia. Most studies (76%) were published between 2011 and 2020, with the earliest being published in 2000. The main focus of 65 studies (84%) were schoolchildren, whereas 12 (16%) studies focused on preschoolers. There were 4 studies that targeted only girls [23,59–61], and 2 only targeted boys [62,63]. Only 10 studies explicitly stated that their aim was to test compensation [23,64–72], and of these studies, 2 specifically mentioned the ActivityStat hypothesis [68,71]. There were 63 studies that used accelerometry to objectively assess PA, 13 used pedometers, and 1 used a heart rate monitor. A SenseWear Armband was used in 2 studies, in addition to an accelerometer, to assess energy expenditure [71,73]. Included studies were assigned to one of six contexts/settings: school-based PA in children and adolescents (*n* = 28), active commuting to school (*n* = 9), daily PA pattern (*n* = 15), physical education lessons (*n* = 16), organized sports (*n* = 5), or others (*n* = 4). With respect to interventional studies, the duration of the intervention varied from one week [63,71] to two years [30,52,53,74,75]. The average duration of the interventions was 36 weeks (standard deviation (SD) = 37 weeks). Investigation of 3 intervention types found that 50% (*n* = 14) were educational, 29% (*n* = 8) were environmental, and 21% (*n* = 6) were multicomponent. Regardless of their study design (interventional or non-interventional), most studies (85%) examined changes in PA within a one-day period.

A total of 39 of the 77 studies, representing 16,297 (40%) children and adolescents, reported statistical indicators that emphasize the probability of compensation. From these 39 studies, 5 reported inconsistent findings in relation to compensation within the sample [61,66,74,76,77]. Furthermore, some studies indicated compensation in one interventional group (higher amount of PA during intervention) but not in the other [31,72]—in girls but not in boys [56,64,78,79], or in boys but not in girls [80]. In Table 2, an overview of all studies supporting compensation (*n* = 39) is presented. With respect to study design, interventional studies indicated compensatory behavior in 75% of studies (representing 76% of participants; *n* = 6477), whereas non-interventional studies supported compensation in only 30% of studies (representing 30% of participants; *n* = 9820) [54,55,64,66,68,73,77–88]. Furthermore, 42% of preschoolers and 40% of schoolchildren showed indicators for compensatory behavior. Measurements conducted with a pedometer indicated compensation in 6938 participants (72%), whereas accelerometer measurements showed indicators for compensation in 9309 participants (30%). In relation to the PA context, school-based PA revealed compensation indicators in 5350 participants, which corresponded to 72% of all participants in this context, followed by active commuting to school (6095 participants; 56%). No compensation was indicated in the sport club context (0%). With respect to intervention duration, in studies with a duration ≥1 year, 100% of participants indicated compensatory behavior. Compensation was supported in all multicomponent interventions (*n* = 2074 participants) and in 64% of all educational interventions (*n* = 2295 participants).

Table 2. Characteristics and compensation or displacement voting of all included articles.

Characteristics	*n* Studies (% of All Studies)	*n* Participants (% of All Participants)	*n* Studies to Support Compensation	*n* Participants to Support Compensation	*n* Studies to Support Displacement	*n* Participants to Support Displacement	All Sources	Compensation Sources
Study design								
Non-interventional studies	49 (64%)	32,310 (79%)	18 (37%)	9820 (30%)	35 (71%)	22,490 (70%)	[23,54,55,58,60,62,64, 66–70,73,77–112]	[54,55,64,66,68,73,77, 79–88]
Interventional studies	28 (36%)	8519 (21%)	21 (75%)	6477 (76%)	10 (36%)	2042 (24%)	[30,31,52,53,56,57,59, 61,63,65,71,72,74–76,113–125]	[30,31,52,53,56,59,61, 63,65,72,74,75,114, 116,118,121–125]
Sample Size								
<500	57 (74%)	10,980 (27%)					[30,52–56,58–60,62–65,67,68,70–74,76–80,82,83,86–88,90–93,95–99,101,103,105, 108,110,111,113–120,122–124]	
>500	20 (26%)	29,849 (73)					[23,31,57,61,66,69,75, 81,84,85,89,94,100, 102,104,107,109,112, 121,125]	
Target group								
Preschool children (3–6 years)	12 (16%)	2188 (5%)	5 (42%)	919 (42%)	7 (58%)	38 (58%)	[65,96,103,110,111, 113,115–117,122–124]	[65,116,122–124]
School children (>6 years)	65 (84%)	38,641 (95%)	34 (52%)	15,378 (40%)	1269 (58%)	23,263 (60%)	[23,30,31,52–64,66–95,97–102,104–109,112,114,118–121,125]	[30,31,52–56,59,61,63, 64,66,68,72–88,114,118,121,125]

Table 2. *Cont.*

Characteristics	*n* Studies (% of All Studies)	*n* Participants (% of All Participants)	*n* Studies to Support Compensation	*n* Participants to Support Compensation	*n* Studies to Support Displacement	*n* Participants to Support Displacement	All Sources	Compensation Sources
Dependent Variable								
Physical Activity	76 (96%)	40,779 (99%)					[23,30,52–86,88–125]	
Energy Expenditure	3 (4%)	333 (1%)					[71,73,87]	
Geographic origin								
Europe	40 (52%)	16,881 (41%)					[30,52,53,56–58,60,61,68,74,75,77,78,80,82–89,93,94,96,97,99–102,104–107,110,111,118,120–122]	
North America	21 (27%)	14,256 (35%)					[23,31,59,64–67,69,70,72,79,90,103,112–117,123,124]	
Australia/New Zealand	10 (13%)	3548 (9%)					[54,55,63,71,73,95,98,108,109,125]	
Asia	6 (8%)	6144 (15%)					[62,76,81,91,92,119]	
PA measurement instrument								
Accelerometer	63 (79%)	31,150 (76%)	32 (51%)	9309 (30%)	36 (57%)	21,841 (70%)	[23,30,52–86,88–125]	[30,52–56,59,61,63–66,68,73–75,77,78,80,82–84,86,88,114,116,118,121–125]
Pedometer	13 (16%)	9629 (23%)	6 (46%)	6938 (72%)	10 (77%)	2691 (28%)	[31,58,70,72,76,79,81,85,90,92,93,109,120]	[31,72,76,79,81,85]
Heart Rate Monitor	1 (1%)	50 (0.1%)	1 (100%)	50 (100%)	0	0	[87]	[87]
Context of PA measures								
School-based PA	26 (34%)	7392 (18%)	19 (72%)	5350 (72%)	10 (36%)	2042 (28%)	[30,31,52,53,56,57,59,61,63,65,71,72,74–76,113–117,119,120,122–125]	[30,31,52,53,56,59,61,63,65,72,74–76,114,116,122–125]
Active commuting to school	10 (13%)	10,733 (26%)	5 (50%)	6175 (58%)	7 (70%)	4558 (43%)	[78,80,81,83,95,104,107–109,118]	[78,80,81,83,118]
Daily PA Pattern	15 (19%)	12,499 (31%)	7 (47%)	1677 (13%)	8 (53%)	10,822 (87%)	[23,54,55,67,69,73,77,82,84,87,92,93,96,103,112]	[54,55,73,77,82,84,87]
Physical Education	17 (22%)	5814 (14%)	7 (41%)	2567 (44%)	12 (75%)	3247 (56%)	[62,64,68,79,85,86,88,90,91,97,99,100,106,110,111,121]	[64,68,79,85,86,88,121]
Sports Club	5 (6%)	2583 (6%)	0 (0%)	0 (0%)	5 (100%)	2583 (100%)	[58,60,94,98,101]	
Others (Locations/Active play)	4 (5%)	1808 (4%)	1 (25%)	528 (29%)	3 (75%)	1280 (71%)	[66,89,102,105]	[66]
Duration of Intervention								
≤one week	2 (7%)	207 (2%)	1 (50%)	51 (25%)	1 (50%)	156 (75%)	[63,71]	[63]
≤one month	1 (4%)	67 (1%)	0 (0%)	0 (0%)	1 (100%)	67 (100%)	[117]	
≤1–2 months	6 (21%)	869 (12%)	5 (83)	573 (66%)	2 (33%)	296 (34%)	[72,76,114,120,122,123]	[72,76,114,122,123]
≤3–4 months	3 (11%)	144 (2%)	3 (100%)	144 (100%)	0	0	[59,65,118]	[59,65,118]
≤5–6 months	6 (21%)	2241 (38%)	3 (50%)	1520 (68%)	4 (67%)	721 (32%)	[31,113,115,116,119,125]	[31,116,125]
≤one year	4 (14%)	2450 (28%)	3 (75%)	1648 (58%)	2 (50%)	802 (32%)	[56,57,121,124]	[56,121,124]
>one year	6 (21%)	2541 (31%)	6 (100%)	2541 (100%)	0	0	[30,52,53,61,74,75]	[30,53,61,74,75,85]
Intervention type								
Educational	14 (50%)	3593 (42%)	9 (64%)	2295 (64%)	7 (50%)	1145 (32%)	[56,57,61,63,71,72,113–117,122,123]	[56,59,61,63,114,116,122,123,125]
Environmental	8 (29%)	2393 (28%)	6 (75%)	2108 (88%)	2 (25%)	285 (12%)	[52,53,65,75,118–121]	[52,53,65,75,118,121]
Multicomponent	6 (21%)	2533 (30%)	6 (100%)	2074 (82%)	1 (17%)	459 (18%)	[30,31,74,76,124,125]	[30,31,74,76,124,125]
Timespan measuring compensation								
Within a day	65 (85%)	37,198 (91%)	35 (54%)	15,567 (42%)	36 (55%)	21,631 (58%)	[23,30,31,52,53,56–59,61–63,65–69,71,72,74–89,91,92,94–96,100,102–125]	[30,31,52,53,56,59,61,63,65,66,68,74–88,114,116,118,121–125]
Between two consecutive days	4 (5%)	904 (2%)	3 (75%)	610 (67%)	1 (25%)	294 (33%)	[54,55,73,97]	[54,55,73]
Across several days	8 (10%)	2727 (7%)	1 (13%)	120 (4%)	8 (100%)	2607 (96%)	[60,64,70,90,93,98,99,101]	[64]

3.3. Results of Methodological Quality Assessment

For quality assessment, we applied the "QualSyst" scoring system with a scoring range of 0–1 [49]. The mean quality score of the included articles was rated as high by both raters (mean = 0.87, SD = 0.10, range 0.5–1). The methodological quality criteria and the proportion of studies fulfilling the criteria are presented in Table 3; more detailed quality assessments of each included article are presented in Electronic Supplementary File S2. Items 5, 6, and 7 were only scored for randomized controlled trials (RCTs).

Table 3. Criteria for the methodological quality assessment and the number (%) of studies that scored points or each criterion.

		Studies Fulfilling the Criteria *n* (%)			
No.	**Item**	**Yes**	**Partial**	**No**	**N/A**
1	Question/objective is sufficiently described?	51 (66%)	26 (34%)	0	0
2	Study design is evident and appropriate?	75 (97%)	2 (3%)	0	0
3	Method of subject/comparison group selection or source of information/input variables is described and appropriate?	64 (83%)	13 (17%)	0	0
4	Subject (and comparison group, if applicable) characteristics are sufficiently described?	50 (65%)	27 (35%)	0	0
5	If interventional and random allocation was possible, was it described?	7 (9%)	9 (12%)	1 (1%)	60 (78%)
6	If interventional and blinding of investigators was possible, was it reported?	4 (5%)	1 (1%)	12 (16%)	60 (78%)
7	If interventional and blinding of subjects was possible, was it reported?	0	1 (1%)	16 (21%)	60 (78%)
8	Outcome(s) and (if applicable) exposure measure(s) is/are well defined and robust to measurement/misclassification bias? Means of assessment are reported?	66 (86%)	11 (14%)	0	0
9	Sample size is appropriate?	70 (91%)	7 (9%)	0	0
10	Analytic methods are described/justified and appropriate?	75 (97%)	2 (3%)	0	0
11	Is some estimate of variance reported for the main results?	36 (47%)	41 (53%)	0	0
12	Controlled for confounding?	44 (57%)	31 (40%)	2 (3%)	0
13	Results reported in sufficient detail?	58 (75%)	19 (25%)	0	0
14	Conclusions supported by the results?	58 (75%)	19 (25%)	0	0

In RCTs, the mean quality score was 0.76 (SD = 0.11) (range 0.5–0.89). In all RCTs, poor blinding of the treatment was evident for both investigators and participants. Overall, the included studies revealed a high quality, and only few studies exhibited a higher risk of bias [64,65,86,120].

4. Discussion

The present systematic review aims to provide a synthesis of studies that have analyzed changes in overall PA, assessed using objective measurements, or compensatory behavior caused by PA increases or decreases in a specific PA domain or during the timespan of one day in children and adolescents.

A total of 77 articles were included that investigated compensation or displacement across various contexts in children and adolescents. Overall, approximately 50% of the included articles found indicators suggesting compensation, and 50% refuted compensational behavior and supported the displacement of inactive time with bouts of activity. Detailed analyses based on study design, target group, instruments, context, intervention duration, and measurement duration were performed, revealing differences in compensation depending on categories. The analyses showed tendencies toward compensation in school interventions (especially with durations lasting longer than 1 year) and tendencies of displacement in the context of weekly organized participation in sport clubs.

It is hypothesized that when PA in one domain or timespan increases, PA in another domain or timespan decreases in order to maintain the constant PA level, as postulated by the ActivityStat hypothesis [22]. In the present analysis, 38 of 77 articles, involving a total of 24,532 participants, refuted the ActivityStat hypothesis and showed an increase in overall PA that resulted from imposed PA in one domain or timespan and absence of a reduction in PA in other domains or timespans. Sustained displacement of inactivity with PA led to an overall increased PA level, as described in the displacement hypothesis. One possible explanation for these increases in overall PA could be that imposed PA stimuli serve as some kind of trigger: PA opportunities in different contexts may stimulate children and adolescents to engage more in physical activities during the entire day [64,70,78,91,105,107].

In our review, we distinguished between interventional and non-interventional studies. A total of 21 interventional studies (n = 6477 participants) showed indicators for compensation, whereas only 18 non-interventional studies (n = 9820 participants) indicated compensatory behavior. This suggests that when the PA of children and adolescents is promoted in an intervention, the participants tend to compensate for the additional bouts of PA within the intervention by decreasing their activity levels during other parts of the day or in other domains so that they maintain their overall PA at a stable level. On the other hand, when children increase their PA levels on their own, without participating in an intervention program (in non-interventional studies), it seems that they do not compensate for this, and ultimately increase their overall PA level. This could be due to the fact that, in these cases, their PA is more likely based on intrinsic motivation that external influences. Furthermore, interventions were mostly offered and performed in (pre)school contexts. Improvements in (pre)school PA can be compensated for by less PA outside of (pre)school [30,31,52,53,56,59,61,63,74–76,114,116,118,121–125]. “It is possible that school-based interventions are too focused on school setting and children and adolescents do not translate the health message on the importance of physical activity at home or in the community” [16]. For school interventions, it has been suggested that the focus should also be placed on changing parental behaviors and awareness for the sake of adopting a sustainable active lifestyle. In addition, multicomponent interventions or interventions that include schools together with families or communities are most effective in changing PA levels [16,29]. In general, interventions are most efficient when they operate on multiple levels [126]. “According to ecological models, the most powerful interventions should (a) ensure safe, attractive, and convenient places for physical activity, (b) implement motivational and educational programs to encourage use of those places, and (c) use mass media and community organization to change social norms and culture.” [127]. Intrapersonal, interpersonal, organizational, community, and public policy factors can influence health behaviors; thus, they consequently counteract compensatory behavior. Even though the literature suggests that multicomponent interventions have been shown to be useful for changing PA behavior, our results contradict this assumption, with the findings of compensatory behavior in all multicomponent studies [30,31,74,76,124,125].

Analysis of interventions pointed out a wide range in terms of intervention duration. All six studies (n = 2541 participants) in which interventions lasted for over one year supported compensation behavior in children and adolescents [30,52,53,61,74,75]. Nevertheless, compensatory behavior in children and adolescents was also identified in interventions that had a duration between one month and one year [31,59,65,72,76,114,116,118,122,123,125]. A possible explanation for this finding could be that interventions which last for a shorter period of time may have little or no effect in changing the PA behavior of children and adolescents due to a lack of time needed to progress through the six stages of change, according to the trans-theoretical model [128]. This means that children and adolescents who accumulate more MVPA during an intervention might continue to be as physically active in their leisure time as they were before the intervention. The longer an intervention lasts, the greater the probability that children and adolescents adapt their PA and become less active in their leisure time; hence, maintaining their overall PA at a stable level.

Almost all studies included in our review captured PA data using pedometers or accelerometers. Only 6 pedometer studies (n = 6938 children and adolescents) reported compensatory mechanisms [31,72,76,79,81,85], whereas children and adolescents (n = 9309) showed compensatory behavior in 32 accelerometer studies [30,52–56,59,61,63–66,68,73–75,77,78,80,82–84,86,88,114,116,118,121–125]. One explanation for this finding could be that pedometers only capture step counts—an index of the number of steps a person took—whereas the overall PA levels for participating individuals remained unknown. Hence, it is likely that compensation is diagnosed through a measured reduction in steps, whereas other shifts in PA levels (e.g., overall MVPA) remain unconsidered. Furthermore, only 1 study out of the 77 analyzed studies investigated energy expenditure using a heart rate monitor and indicated compensation [87].

In addition to interventions in a school context, there are two other settings in which children and adolescents are physically active. Only 57% of children and adolescents who actively commute to school showed indicators for compensation [78,80,81,83]. Active commuting and the independent mobility of children provide additional opportunities for spontaneous play [107] and enable other active behaviors [129,130]. This can lead to an increase in overall PA, which therefore supports the displacement theory.

In the PE context, only 32% of the participants indicated compensatory behavior [64,68,79,85,86,88]. PE classes should provide an opportunity for children and adolescents to engage in PA and to develop knowledge about and attitudes toward developing an active lifestyle [131], which could lead to displacing inactivity with active behavior. Interestingly, two articles, involving 365 participants, investigated the impact of different amounts of PE per week on overall PA levels in children and adolescents. From their findings, it can be summarized that more PE per week is not necessarily effective for increasing the total PA, because the PA in PE classes is often compensated for by less activity outside of the school setting [68,86]. Consequently, future studies should assess what the right amounts and intensities of PA during PE classes would be in order to avoid compensation outside of school.

Finally, our detailed analyses revealed one PA domain in which an increase in activity levels was not found to lead to compensation, but instead, to displacement: when engaging in organized sport clubs, children and adolescents do not compensate their PA levels by being less active after the training sessions [58,60,94,98,101]. Sport clubs represent a health-promoting setting and support children and adolescents in living an active lifestyle outside sport clubs [132]. Furthermore, sport programs can provide beneficial access to and resources for recreational activities [98]. Thus, participation in sport clubs serves as an additional factor for increasing overall PA and can displace sedentary behavior.

Compensatory behavior occurs after a PA increase or decrease in one domain or timespan in order to maintain a stable overall PA level. Almost all studies in this review revealed that a PA increase in one domain or timespan is followed by a PA decrease in another domain or timespan, which is negatively connoted. Nevertheless, there exists one study [79] in our review, where compensatory behavior was found to occur after a PA reduction—leading to compensation being positively connoted.

4.1. Implications

This review of compensation for PA in children and adolescents provides inconsistent results relating to compensation. Consequently, further research is needed to better understand compensatory mechanisms, and a recommendation is made for future studies to investigate PA behavior over a period of a few days using an objective measurement method. In addition, participants should complete a questionnaire or keep a diary in order to terminate and locate their activities and to obtain information about the reasons for their PA behavior. Social support plays an important role for sufficient PA in children and adolescents. Thus, PA behavior and attitudes of family and friends can influence one's own PA and determine compensatory behavior. Additional subgroup analysis, including an examination of differences in PA by gender, age, weight status, socio-economic status (SES), and ethnicity, could provide more information about compensatory behavior. Gender differences have already been seen in a few of the included studies with inconclusive results [56,64,78,80]. Additionally, various SES analyses indicate different environmental, social, and educational circumstances [133,134]. Hence, SES is an important predictor of PA in children and adolescents [133] and can influence compensatory behavior. Unfortunately, none of the included studies investigated compensatory behavior separately for different SES. It is hypothesized that children and adolescents with lower SES compensate more often than individuals with higher SES. It would also be interesting to further investigate the setpoint for "ActivityStat" or possible differences depending on age, season, or energy intake. Through an experimental design, future studies could investigate when this setpoint is reached and whether there are differences. Furthermore, there are currently no existing theories that deal with the timeframe for compensation. It is hypothesized that the timeframe for compensation is unlikely to be day-to-day [22]. Currently, the timeframes in the studies examined in our review are random. Finally, combined measurements of energy expenditure and PA should be used to obtain more detailed and reliable information about compensatory mechanisms.

Practical implications refer to interventional studies: in addition to active PA promotion, it is important to improve awareness in children and adolescents, as well as in their parents, regarding the importance of PA, as well as to encourage them to be physically active at home during their leisure time. This is necessary in order to avoid compensation that occurs when PA at home and/or in the family environment is reduced after increases in PA levels take place during interventions in, for example, the school setting.

4.2. Strengths and Limitations

The main strength of this review is that we exclusively included studies that objectively measured PA, including measures that directly assessed one or more PA dimension (e.g., frequency, intensity, time, and type) and captured a variety of measures, such as step counts, activity minutes, and PA intensity [45]. An additional strength lies in the fact that the systematic search of relevant primary studies employed several electronic databases and a comprehensive list of search strings. Furthermore, the reference lists of all included studies were manually checked in the search for additional relevant studies. Our search strategy was broad enough to enable us to identify relevant studies as well as to include those studies that did not analyze PA compensation as their main objective. In contrast to Gomersall, Rowlands, English, Maher, and Olds [22], we did not only include studies that made explicit reference to compensation. Instead, we analyzed studies investigating changes in overall PA and in different domains or time segments for compensatory mechanisms. Another strength is the inclusion of a wide range of different settings in which PA plays an important role.

A limitation of this review relates to the variety in the study designs of the included studies, which made a comparison of the results difficult. Additionally, some studies only allowed between-subject analyses, which, in turn, only enabled conclusions about compensation to be obtained from a comparison of PA levels between two groups. For better understanding of compensatory mechanisms, within-subject analyses could provide stronger results. Another limitation is that there were different PA segments in the reviewed studies, which made it difficult to compare them all.

5. Conclusions

This systematic review provided inconclusive results regarding potential compensatory activity behavior after changes in PA levels in one domain or during a timespan in children and adolescents. Overall, 39 studies (*n* = 16,297 children and adolescents) that were included in this review did exhibit indicators of compensation. In summary, the synthesis of the included studies revealed a tendency for compensatory behavior in the context of interventions, especially in interventions with a long duration (<1 year). Furthermore, children and adolescents who regularly participated in organized sports showed no indicators for compensatory behavior. In order to verify the results of the present review, further investigations are needed.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/children9030351/s1, Table S1: Data extraction of included studies, Table S2: Quality Assessment of included studies.

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Summary

The present review included a total of 77 peer-reviewed articles that analyzed changes in overall PA with multiple methodological approaches. Overall, 39 studies (*N*=16,297 children and adolescents) that were included in this review exhibited indicators of compensation. Sub analyses separated by study design, participants, measurement instrument, PA context, and intervention duration also showed mixed results towards an indication of compensation. In summary, the synthesis of the included studies revealed a tendency for compensatory behavior in the context of interventions, especially in interventions with a long duration (>1 year). Furthermore, children and adolescents who regularly participated in organized sports showed no indicators for compensatory behavior.

Consequences

As this systematic review provides inconclusive results, and to verify the tendencies developed from the present review, further investigations are needed to better understand compensatory mechanism. In more detail, future studies should investigate PA behavior over a period of a few days using a device-based measurement method. Additional subgroup analysis, including an examination of differences in compensatory behavior by gender, age, weight status, SES, and ethnicity, could provide more information about mechanism of compensatory behavior. Furthermore, there are currently no existing theories that deal with the timespan for compensation. It is hypothesized that the timespan for compensatory responses is unlikely to be day-to-day (Gomersall et al., 2013). Currently, the timespans in the studies examined in our review are random. Within the following study, that is based on a secondary accelerometer data analysis (Manuscript D) we wanted to address these research gaps.

4.1.3 Manuscript D: Compensation of Overall Physical Activity in (pre)Adolescent Girls – the CReActivity Project

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Introduction

The systematic review provided inconsistent results and identified various research gaps. In the first step, we therefore focused in the present study on sociodemographic differences with regard to compensatory behavior. Gender differences have already been seen in a few of the included studies with partial inconclusive results (Alderman et al., 2012; Cooper et al., 2003; Schneller et al., 2017). Additionally, various SES analyses indicate different environmental, social, and educational circumstances (Gidlow et al., 2016; Schmidt et al., 2020b). Hence, SES is an important predictor of PA in children and adolescents (Gidlow et al., 2016) and may also influence compensatory behavior. Unfortunately, none of the included studies in the systematic review investigated compensatory behavior separately for different SES. It would also be interesting to further analyze possible age-related differences within an age group. Existing studies so far identified compensatory behavior across all age spans from preschool children (Alhassan et al., 2012) to adolescents (Kek et al., 2019a; Nigg et al., 2022) with no age related analysis within one age group. Furthermore, timespan for activity compensation is unknown. Gomersall et al. (2013) hypothesized that the timespan for compensation is unlikely to be day-to-day. Currently, the timespans in the studies examined in our review are random. Having these research gaps in mind, we conducted a secondary data analysis with the aim to investigate in (pre)adolescent girls, (1) whether sedentary time during the morning is compensated by active behavior in the afternoon and (2) whether sedentary time during the week is compensated by active behavior during the weekend. Additionally, we aimed to examine whether compensatory behavior is moderated by SES, age and/or weight status.

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RESEARCH Open Access

Compensation of overall physical activity in (pre)adolescent girls – the CReActivity project

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Abstract

Background: According to the ActivityStat hypothesis more physical activity (PA) in one timespan is compensated by increased sedentary time (ST) in the following timespan and vice versa to maintain an overall stable PA level. Until now, existing literature revealed inconsistent results regarding compensatory behaviour across children and adolescents. Thus, the aim of the present study is (1) to investigate whether ST in the morning is compensated by active behaviour in the afternoon and (2) whether ST during the week is compensated by active behaviour during the weekend in (pre)adolescent girls. Additionally, we aimed to differentiate between positive and negative compensatory behaviour and examine whether it is moderated by socioeconomic status (SES), age or weight status.

Methods: The participants were 370 sixth grade school girls (mean age 11.6 years) from Munich that participated in the CReActivity study, a school based intervention study aiming to identify the mechanisms of behavioural changes in PA among girls. ST and PA were measured over seven consecutive days using accelerometery. Descriptive determination of compensatory behaviour, as well as Bayesian multivariate multilevel analysis were conducted with data clustered on the individual (ID), class and school level.

Results: Descriptive analysis revealed rather constant compensatory behaviour of about 60% for after-school days and weekends over all observation points. However, regarding all girls, compensation was predominantly negative. Differentiated analysis indicated that all girls with low ST levels in the morning or on weekdays, compensated for this behaviour with lower PA levels in the afternoon or on weekends. Multilevel covariate analysis indicated great variability between the participants. Furthermore, differences in compensatory behaviour can also be seen on class and school levels. Interestingly, PA compensatory behaviour is not associated with age, weight status or SES.

Conclusion: Our findings could neither confirm nor reject the ActivityStat Hypothesis. Overall, due to the great variability across the girls, it seems that compensation depends on individual factors. In the future, to prevent negative compensation, school-based interventions that have the potential to provide opportunities to be physically active, should not neglect (pre)adolescents' leisure time behaviour.

Trial Registration: DRKS00015723 (date of registration: 2018/10/22 retrospectively registered).

Keywords: Compensation, Girls, (pre)adolescents, Negative, Positive, Physical activity

Background

Physical activity (PA) is described as "any bodily movement produced by skeletal muscles that result in energy expenditure" [1] and is an important source for overall health in children and adolescents [2]. The long-term effects of PA are well documented and indicate an increase in physical fitness as well as improved

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cardiovascular [3] and cardio metabolic [2, 3] health. Besides the physiological health benefits, PA is associated with better mental health [4, 5]. In order to support children and adolescents in achieving these benefits, the World Health Organization (WHO) developed PA recommendations for children and adolescents, stating a desired average of 60 min/day of moderate-to-vigorous intensity, mostly aerobic PA, across the week [6]. Furthermore, vigorous-intensity aerobic activities, as well as those that strengthen muscle and bone, should be incorporated at least 3 days a week [7]. Nevertheless, PA levels of children and adolescents in many regions worldwide do not meet the WHO recommendations [8–10]. Specifically, with increasing age, the prevalence of guideline compliance seems to decrease [11–13], and the difference between boys and girls consistently widens from childhood to adolescence [14]. Therefore, (pre)adolescent girls reveal lower PA levels compared to boys at this age [9, 15–18] and represent a high-risk population related to PA [19].

In addition to age and gender, further sociodemographic variables must be taken into account to understand PA levels in children and adolescents. In particular, regarding the socioeconomic status (SES) of the parents, including available resources and family lifestyle, various studies have shown that children in all age groups from families with a higher SES are more physically active compared to children from families with a lower SES [20–22]. Results from the German MoMo-Study confirmed these results with regards to total PA and organised PA. Nevertheless, in settings such as unorganised sports or extracurricular sports an inverse relationship was found [23]. In addition to the influence of SES and age, (pre)adolescents with higher weight status are less active than children with lower weight status [1224].

Numerous efforts to promote PA among children exist across different settings, including schools, family environment or local community settings, but efficacy in the short and long term has widely varied [25, 26]. Additionally, the WHO stated that global efforts seem to miss the goal and that further action is needed [10].

One reason for the limited effects of current efforts could be the mechanisms of compensation as postulated in the ActivityStat hypothesis [27]. The assumptions of this hypothesis are generally not taken into account when promoting PA in children and adolescents. It focuses on the potential effect of the intrinsic biological control that underpins PA and energy expenditure (EE): an imposed increase or decrease in PA in one domain/timespan might induce a compensatory change in the opposite direction, i.e., in another domain/timespan, in order to maintain a stable level of PA or EE over the time [27]. Compensation can occur by increasing or decreasing the intensity, frequency and/or duration of time spent in PA or inactivity [28]. Compensation can occur as positive or negative. Positive compensation is defined as an increase in PA levels in one time span following low PA levels in another time span. In particular, Tudor-Locke, Lee [29] indicated higher PA levels after school in girls that had low PA levels in school. Negative compensation is defined as a decrease in PA levels following high PA levels. This can often be seen for instance after interventions in which PA levels are increased in one timespan (e.g., in interventions promoting PA at school) [30–37].

Gomersall, Rowlands [27] were the first to publish a review about compensatory behaviour in children, adolescents and adults. The authors provided an overview of experimental studies investigating compensation with objective and subjective measurement methods, but the results were inconclusive. On this basis, our own review of compensation or displacement in children and adolescents [38] updated the existing overview by including diverse study designs with solely objective measurements and the focus on children and adolescents. Additionally, in our review we differentiated between various subgroups and summarised existing literature related to compensatory behaviour in children and adolescents across different contexts (physical education (PE), interventions, daily PA, organised sports club participation, active travel) [38]. Our data synthesis revealed that half of the studies support and half of the studies refute compensation of PA. A review investigating compensation in youths and adults revealed inconsistent results, but with one third of youths showing compensatory behaviour [39]. Daily PA includes PA levels across a regular school day without any PE, interventions or sports club participation. In this context, half of the studies indicated a negative compensatory behaviour [40–46]. Furthermore, based on sociodemographic variables, potential moderators of compensation were investigated in only a few included studies. To date, studies focused on different age groups [41, 47, 48] and gender [29, 47–51]. Compensatory behaviour was indicated across all age spans from preschool children [52] to adolescents [48, 53] as well as in boys and girls, and there are even a few studies supporting compensation only in girls and not in boys [29, 49, 50, 54]. Related to weight status, studies revealed no differences in compensatory behaviour across normal and overweight children and adolescents [33, 36, 55–57]. To the best of our knowledge, other moderators such as SES have not been yet investigated within a context of compensatory behaviour.

A large body of scientific literature on the compensatory behaviour of PA is available but shows inconclusive results. Furthermore, previous research has focused sparsely on differences in compensatory behaviour related to sociodemographic variables. The aim of the present study is thus to investigate, in (pre)adolescent girls, (1) whether sedentary time (ST) during the morning is compensated by active behaviour in the afternoon and (2) whether ST during the week is compensated by active behaviour during the weekend. Additionally, we aim to examine whether compensatory behaviour is moderated by SES, age and/or weight status.

Methods

Study design

The present study is a secondary data analysis of baseline data from the CReActivity project, a school based intervention study aiming to identify the mechanisms of behavioural changes in PA among girls through a self-determination theory-based intervention in PE [58]. The study was approved by the Ethics Committee of the Technical University of Munich (protocol code 155 / 16S) and was in accordance with the 1964 Declaration of Helsinki. All participants as well as one of their parents provided written informed consent for study participation.

Participants

All secondary schools (Realschulen) in and around Munich were contacted one year before the CReActivity study was implemented. Inclusion criteria for the study were secondary schools and female-only sixth-graders who participated actively in mono-educated PE. Exclusion criteria only existed on a school level and included PE lesson for boys, no gym as well as insufficient or unqualified teachers. Principals and parents' councils from 15 schools provided informed consent. The researchers gave the letter asking for consent to participate in the data collection process to the PE teachers, who distributed them to the children. The children then forwarded the letters to their parents, as both children and their parents had to provide written informed consent. Five hundred and seven sixth-grade female students from 32 single-sex/gender PE classes were enrolled in this study. Valid baseline data was collected from 370 girls aged 9–14 years.

Data collection

Data collection took place between October and December in the school years 2017/2018 and 2018/2019, respectively. The questionnaire data was collected during PE lessons held in the gym. After providing instructions, a member of the research team distributed the accelerometers to all eligible students and supervised the completion of the paper–pencil questionnaire. After that a research assistant assessed the anthropometric data using a weight scale and stadiometer. The girls were asked to wear an accelerometer for 7 consecutive days. On week- and weekend days, girls were advised to put the devices on in the morning after getting out of bed and wear them until 9 p.m. or just before bedtime, except during water-based activities. One week later, the PE teacher collected the devices from the students and forwarded them to the research team.

Measurements

Socioeconomic status

Participants reported parents' occupations and job descriptions. The answers were classified by referring to the International Socioeconomic Index of occupational status (ISEI), which is based on the International Standard Classification of Occupation 2008 (ISCO-08) [59]. When the jobs of both parents could be classified, the job with the higher ISEI was considered (HISEI). Vague answers made a definite classification impossible, reducing the number of HISEI values. Written answers of the parental SES were coded by a trained committee of four student research assistants according to the International Standard Classification of Occupation 2008 (ISCO-08). After revision by two researchers, open conflicts were solved and coded under consideration of the International Socio-Economic Index (ISEI) score [59].

Age and weight status

Based on the self-reported birth date participants' age on the first school day of the respective school year was calculated in years. Stature was measured to the nearest 0.1 cm and body weight was measured to the nearest 0.1 kg. Participants were measured wearing sports clothes but without shoes. Body mass index (BMI, $kg*m^{-2}$) was calculated as an indicator of weight status.

Physical activity and sedentary time measurement

PA and ST were measured with accelerometers (ActiGraph models GT3X – wGT3X-BT; Pensacola, FL, USA). The devices were worn on the right hip with an elastic belt. The sampling rate was set to 30 Hz. Further details have previously been described in detail [60].

Physical activity-related environment

Environmental factors of relevance for PA were assessed with ten items of the 'Assessing levels of Physical Activity and Fitness at Population level' (ALPHA) short scale [61]. The scale has been translated and was pilot tested with sixth grade students in Germany. In the validation study the ALPHA short exhibited a stable test–retest reliability with an intra-class correlation coefficient (ICC) of 0.73 [61]. The questionnaire includes ten statements related to the neighbourhood built environment. This means the area around participants' home that can be reached on foot within a maximum of 15 min. Girls were able to answer yes, no or don't know. The higher the value, the more places can be reached by foot within the walkable neighbourhood (15 min).

Accelerometer data reduction

ActiGraph data were downloaded and processed into 1 s epochs using ActiLife. The algorithm by Choi, Liu [62] classifies 90 consecutive minutes of zero counts per minute as non-wearing bouts, allowing for up to 2 min of less than 100 counts per minute (cpm) (within 30 min). Participants' PA data were regarded as valid if at least 8 h of wear time were recorded on at least three weekdays and one weekend day. Weekends contained data from 7 a.m. to 9 p.m., while weekdays were separated into morning from 7 a.m. to 1 p.m. and afternoon from 1 p.m. till 9 p.m.. According to the cut-points by Hänggi, Phillips [63], we estimated the daily average ST (< 180 cpm), light PA (LPA) (181–3360 cpm) and moderate-to-vigorous PA (MVPA) (> 3360 cpm) for each participant. For the statistical analyses, relative wear time, i.e. proportions of ST, LPA, and MVPA, was calculated.

Statistical analysis

Analytic strategy

The determination of compensatory physical activity behaviour (CPB) is first performed with the descriptive data operationalising formulas for different types of compensation. In a second step, we fit inferential models to analyse the impact of covariates on the physical activity levels in the compensatory time periods.

Descriptive statistics

Descriptive statistics were calculated for all study variables, with means (*M*) and standard deviation (*SD*) for continuous variables. For afternoon vs. morning analysis, the 370 girls produced wear time for seven days with 1,146 valid observation points, whereas weekday and weekend analyses were conducted with one value from each girl. In this context, observation points refer to the fact that the girls can produce values on several days in the morning and in the afternoon over a period of seven days.

Determination of CPB

CPB is directly derived from the relative PA and ST data and can be defined in terms of positive and negative compensations. In this context, compensation is positively negotiated when higher ST levels in one time-period are followed by higher PA levels in another. On the other hand, a negative compensation describes lower ST in one time-period being compensated by lower PA in the other. CPB can be applied to afternoon (after school) PA/ST behaviour with respect to morning behaviour, and weekend behaviour with respect to week-day behaviour. We defined CPB to be displayed by the participants if the respective physical behaviour pattern in one time-period was at least 1.645 standard deviations different (90% CI) from the other pattern in the other time-period. This relationship is mathematically expressed in the following equations:

$$\text{Positive compensation}: \text{ if } ST_{afternoon} < ST_{morning}, \text{ then } (LPA_{afternoon} + MVPA_{afternoon}) - (LPA_{morning} + MVPA_{morning}) > 1.645 \times sd(LPA_{morning} + MVPA_{morning})$$

$$\text{Negative compensation}: \text{ if } ST_{afternoon} > ST_{morning}, \text{ then } (LPA_{afternoon} + MVPA_{afternoon}) - (LPA_{morning} + MVPA_{morning}) < 1.645 \times sd(LPA_{morning} + MVPA_{morning})$$

$$\text{Positive compensation}: \text{ if } ST_{weekend} < ST_{weekday}, \text{ then } (LPA_{weekend} + MVPA_{weekend}) - (LPA_{weekday} + MVPA_{weekday}) > 1.645 \times sd(LPA_{weekday} + MVPA_{weekday})$$

$$\text{Negative compensation}: \text{ if } ST_{weekend} > ST_{weekday}, \text{ then } (LPA_{weekend} + MVPA_{weekend}) - (LPA_{weekday} + MVPA_{weekday}) < 1.645 \times sd(LPA_{weekday} + MVPA_{weekday})$$

To better understand compensatory behaviour, the equations for the determinations of CPB are illustrated in the following figures. In addition to the compensatory behaviour, we illustrate what non-compensatory behaviour looks like (Fig. 1).

Covariate analysis

To investigate the association between relative ST in the morning and relative PA behaviour in the afternoon (for weekend analysis: relative ST during the week and relative PA behaviour on the weekends) with respect to weight status, age and SES, we fitted a series of multivariate multilevel models. These models were controlled for the built environment factor. We chose a Bayesian approach as it gives more flexibility in the model specification and outperforms maximum likelihood estimation [64]. To ease model convergence and the interpretation of the results, all continuous variables have been normalised (z-standardised). Thus, the scale-free parameter estimates can also be interpreted as effect-sizes.

Since the data are clustered into multiple levels, i.e. observations nested in individuals, who are in turn nested in classes and schools, varying intercepts have

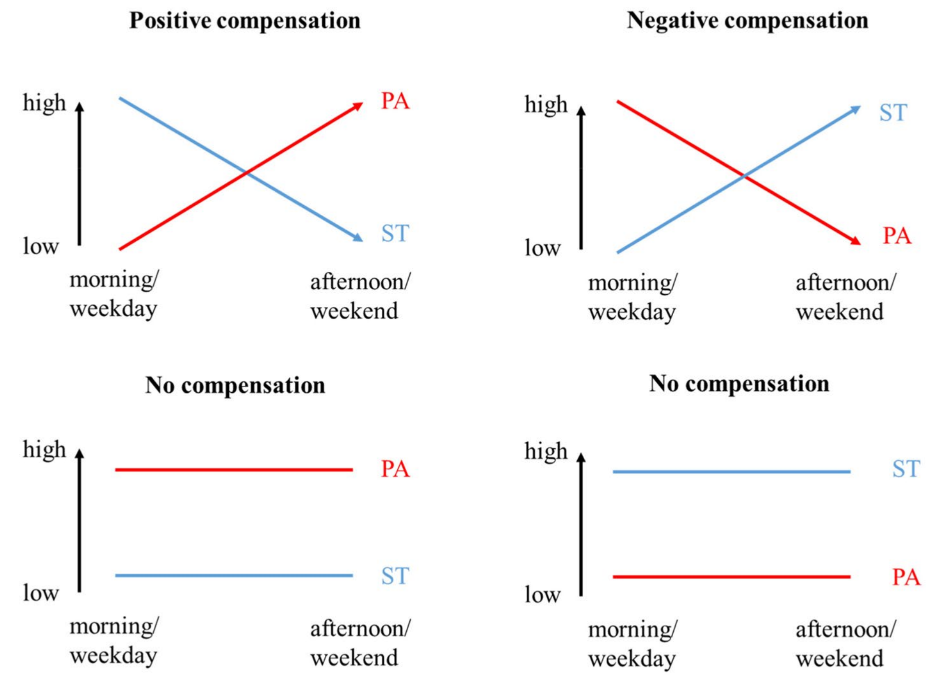

Fig. 1 Illustration of positive, negative and no compensation throughout the whole day/week

Table 1 ICC(1) for LPA and MVPA in the afternoon and on the weekend across different clusters

	LPA			MVPA		
	ID	*Class*	*School*	*ID*	*Class*	*School*
Afternoon	0.52	0.34	0.30	0.28	0.034	0.014
Weekend	[a]	0.41	0.31	[a]	0.09	0.06

[a] For weekday-weekend analyses, observations on the individual level were aggregated to relative frequency scores for the two respective periods and thus no ICC can be determined

been calculated for each level. ICC(1) determines the amount of variance that can be explained by simply clustering the data on the respective level. If the correlation is near zero, the observations within clusters are no more similar than observations from different clusters, hence clustering is not necessary. A threshold of ICC(1) > 0.05 is used to determine whether or not the cluster-level should be accounted for (Table 1).

In addition, we also freely estimated the slope parameters for each predictor on student (ID), class, and school levels and gradually reduced complexity in the model by removing those random effects on the class and school levels that were not credibly different from zero. The final models were chosen according to best model fit, using Markov Chain Monte Carlo (MCMC)-performance as an indicator. As all response variables are skewed, we fitted the data using a skew-normal distribution as a likelihood function, which captures the data better than the normal distribution.

The general model for the afternoon vs. morning analysis using brlm-syntax is as follows:

$$\begin{aligned} &\mathrm{brm}(\mathrm{mvbind}\left(\mathrm{LPA}_{\mathrm{afternoon}}, \mathrm{MVPA}_{\mathrm{afternoon}}\right) \sim \mathrm{ST}_{\mathrm{morning}} \\ &\quad + \mathrm{ses} + \mathrm{environment} + \mathrm{bmi} + \mathrm{age} \\ &\quad + (1 + \mathrm{ST}_{\mathrm{morning}} + \mathrm{ses} + \mathrm{environment} + \mathrm{bmi} \\ &\quad + \mathrm{age}|j|\mathrm{id}) + \left(1 + \mathrm{ST}_{\mathrm{morning}} + |k|\mathrm{class}\right) \\ &\quad + (1 + \mathrm{ST}_{\mathrm{morning}} + |l|\mathrm{school}) \end{aligned}$$

where LPA_afternoon as well as MVPA_afternoon are the dependent variables and everything on the right side of ~ specifies predictors (ST_morning, SES, environment, weight status and age). For both the observation and group level terms the + is used to separate effects from each other. Group level terms are of a form (coefficient | group) where a coefficient contains one or more variables whose effects are assumed to vary with the levels of the grouping factor given in the group. In our sample, we differentiated between ID, class and school level. On a school and class level, only the association of LPA_afternoon/ MVPA_afternoon and ST_morning is analysed related to varying effects. Intercepts for the respective levels are denoted with the constant 1.

This term was adjusted for weekend analyses, containing LPA_weekend as well as MVPA_weekend as dependent variables and ST_weekday as one of the predictors. The rest is treated in the same way as in the first model, except on the ID-level, we simplified the formula by reducing the variables to ST_weekday:

$$\text{brm}(\text{mvbind}(\text{LPA}_{\text{weekend}}, \text{MVPA}_{\text{weekend}}) \sim \text{ST}_{\text{weekday}} + \text{ses} + \text{environment} + \text{bmi} + \text{age} + (1 + \text{ST}_{\text{weekday}}|\text{p}|\text{id}) + (1 + \text{ST}_{\text{weekday}}|\text{q}|\text{class}) + (1 + \text{ST}_{\text{weekday}}|\text{r}|\text{school})$$

To determine statistical significance, a 95% high density interval (HDI) was used for weekdays (morning-afternoon) to display posterior distributions. Due to the skewness of the response variables, the posterior distributions are not symmetrical and the HDI captures this better than equally-tailed intervals [65]. Yet, the HDI can be interpreted in the same way as equal-tailed summary credible intervals. MCMC simulation indicated a sufficient number of independent draws to warrant 95% credibility. For the weekday-weekend analysis, MCMC quality was sufficient to use the 90% HDI to indicate significant findings [65]. Additionally, the 60% HDI trends were calculated.

Statistical programs

All statistical tests and illustrating graphs were performed using R version 4.1.1 [66] and Excel version Professional Plus 2016 [67]. Inferential models were fit using the R-package "brms" [68]. Summary statistics and highest density intervals have been calculated with "parameters" [69], and plots have been generated using "bayesplot" [70].

Results

Sociodemographic data

Valid accelerometer data from 370 girls with a mean age of 11.6 ($SD = 0.5$) years were available (Table 2). Regarding the weight status of the girls, the mean BMI value was 19.5 kg · m^{-2} ($SD = 3.7$). Related to the classification of Kromeyer-Hauschild, Wabitsch [71], which provides percentile curves of the BMI of a representative sample of children and adolescents in Germany, the BMI mean value of 19.5 kg · m^{-2} indicates the 75th percentile in adolescent girls. With possible values between 16 and 90 [59], the score in our sample ranged between 16 and 89, and the mean SES in our study was 50.9 ($SD = 16.0$), indicating an overall medium SES with respect to the included girls. The built environmental factors of participants ranged from 0 to 10 with a mean value of 6.8 out of a possible 10.

Table 2 Descriptive data from included participants (Mean (SD))

Sample (*n* = 370)	**Mean (SD)**
Sociodemographic data	
Age (years)	11.6 (0.5)
Body mass index (kg · m^{-2})	19.5 (3.7)
Socioeconomic status	50.9 (16.0)
Environmental factor	6.8 (2.2)
Physical activity on weekdays	
ST in the morning (min/morning)	283.3 (54.9)
ST in the afternoon (min/afternoon)	255.3 (61.7)
LPA in the morning (min/morning)	101.5 (37.9)
LPA in the afternoon (min/afternoon)	85.5 (33.2)
MVPA in the morning (min/morning)	44.2 (16.9)
MVPA in the afternoon (min/afternoon)	42.7 (22.0)
Physical activity on weekend days	
ST (min/day)	430.4 (97.5)
LPA (min/day)	150.8 (55.1)
MVPA (min/day)	30.7 (11.6)

Descriptive analysis of sedentary behaviour and physical activity

PA and ST levels were calculated for weekdays as well as for weekend days (Table 2). We analysed relative PA and ST levels due to the various wear times of the accelerometer for girls (Fig. 2).

Morning-time vs. afternoon-time during the week

During the mornings, the girls spent 66.21% per day being sedentary and in the afternoon the amount was similar at 66.49%. In the morning, LPA levels were slightly greater than in the afternoon (23.54% vs. 22.29%) whereas MVPA levels were slightly higher in the afternoon (10.27% vs. 11.24%, see Fig. 3).

Weekdays vs. weekends

During weekdays, 66.06% of the (pre)adolescents' time was spent on ST and during the weekend this amount was similar with 66.29% spent being sedentary. Furthermore, relative values indicated similar LPA levels in (pre) adolescent girls between weekdays and weekend (23.23% vs. 23.24%) (see Fig. 2).

Descriptive analysis of compensatory behaviour

To assess compensatory behaviour, descriptive analyses were conducted related to the morning and afternoon period as well as the weekend and weekdays (see Figs. 3).

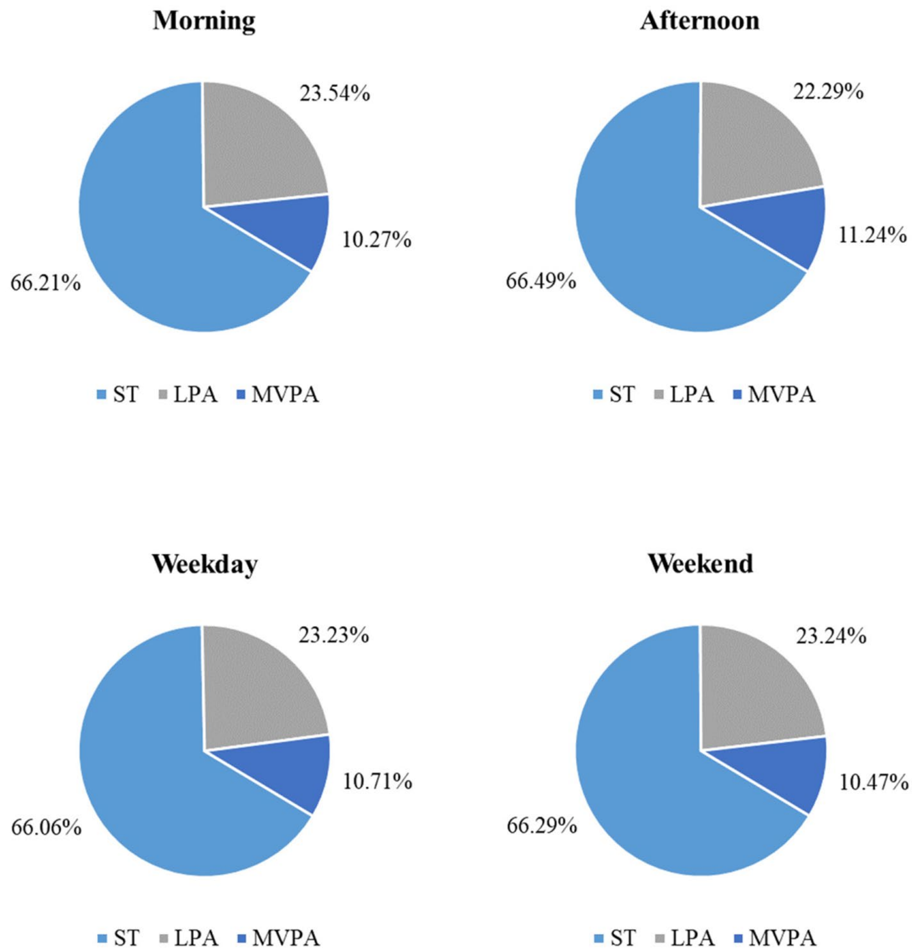

Fig. 2 Relative time of sedentary behaviour and physical activity in the morning and afternoon and on weekdays and the weekend

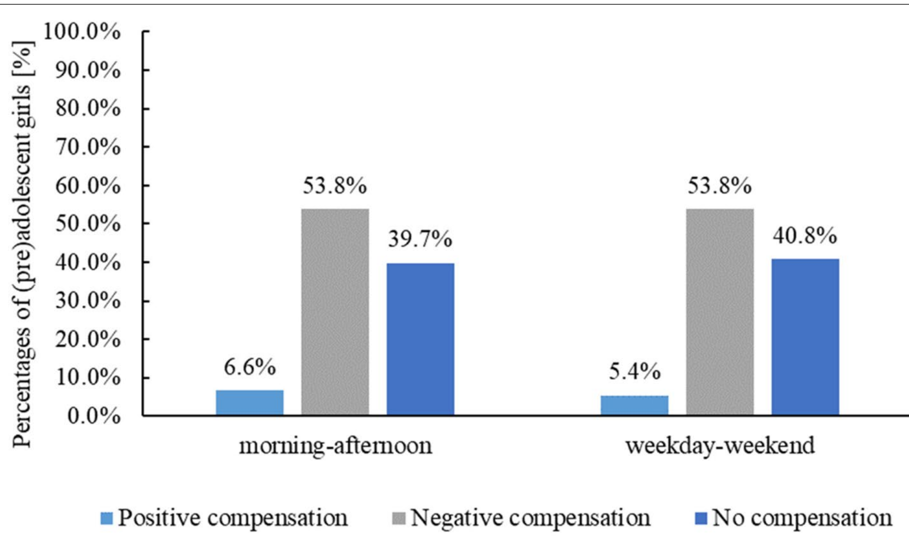

Fig. 3 Negative, positive or no compensatory behaviour. Percentages of participants showing or not showing a compensatory behaviour at all observation points in the afternoon (left) and on the weekends (right)

Morning-time vs. afternoon-time during the week

Descriptive analyses indicated compensatory behaviour in 689 of 1,142 (60.4%) valid observation points during weekdays with 6.6% positive and 53.8% negative points of compensation (Fig. 3). Differentiated analysis indicated relatively more ST in morning compared to the afternoon in 528 observations, in which, as a consequence, allowed positive compensation to occur. In our sample, in 75 of these 528 observation points (14.2%) positive compensatory behaviour with more LPA and MVPA in the afternoons was seen. On the other hand, all observation points in girls with more PA in the morning, which is the basis for a negative compensation, showed a negative compensation of the activity with more ST in the afternoons (Fig. 4).

Weekday vs. weekend

On weekend days, compensation was revealed in 219 of 370 girls (59.2%) with 5.4% positive and 53.8% negative compensatory behaviour (Fig. 3). Overall, 171 girls had more ST during weekdays and thus the potential to compensate positively, but only 11.7% ($N = 20$) actually displayed more LPA and MVPA on weekend days. On the other hand, all girls ($N = 199$) with higher PA levels during weekdays compared to weekend days, i.e., those who were particularly positioned to negatively compensate, demonstrated this behaviour. This means, that they compensated the higher PA-levels during the week with higher ST on weekend days (Fig. 5).

Inferential analysis of physical activity

Morning-time vs. afternoon-time during the week

Inferential statistical analyses investigated if sedentary time in the mornings (ST1) would predict PA in the afternoons (LPA2, MVPA2), dependent on SES, age, and weight status (Table 3).

Fixed effects for the LPA2-model showed a negative, medium to large association between ST in the morning and LPA in the afternoon (β = -0.44; 95% HDI = [-0.56, -0.31]) which indicated that girls with more ST in the morning showed lower LPA in the afternoon. Furthermore, a small negative association was estimated between weight status and LPA in the afternoon with a low effect size (β = -0.10; 95% HDI = [-0.13, -0.07]). SES was not associated with LPA behaviour in the afternoon in (pre)adolescent girls, however, a

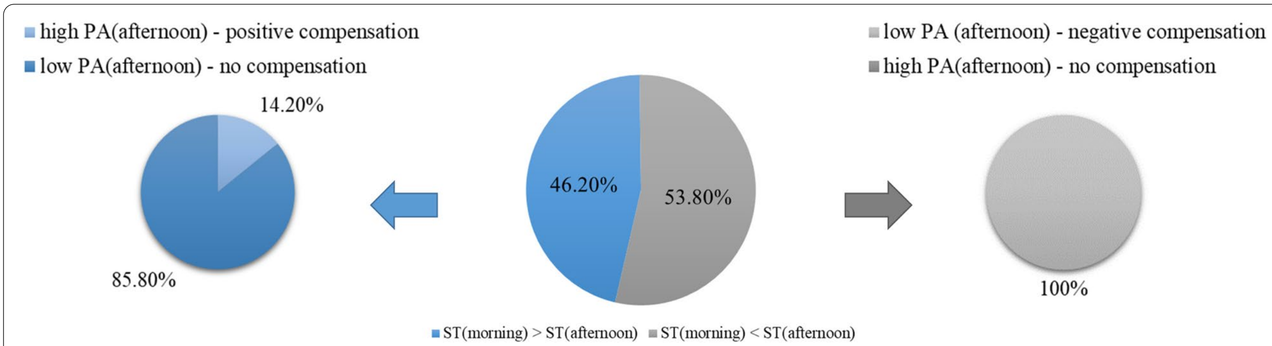

Fig. 4 Differentiated analysis of compensatory behaviour. Percentages of observation points indicating a negative or no compensatory behaviour after having low ST levels in the morning (left) and percentages of observation points indicating a positive or no compensatory behaviour after having high ST levels in the morning (right)

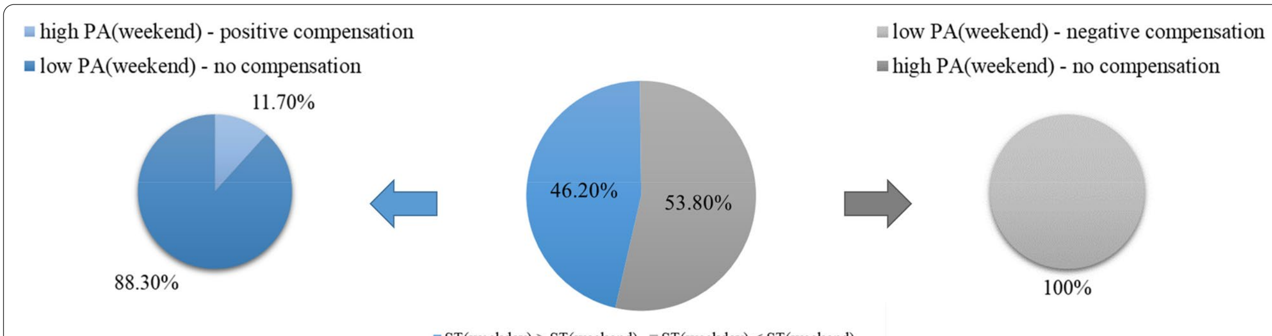

Fig. 5 Differentiated analysis of compensatory behaviour. Percentages of observation points indicating a negative or no compensatory behaviour after having low ST levels during weekdays (left) and percentages of observation points indicating a positive or no compensatory behaviour after having high ST levels during the weekdays (right)

Table 3 Associations on an observational level between PA levels in the afternoon and ST in the morning and sociodemographic variables

Parameter	Median	60% HDI	95% HDI	Pd (%)	Rhat	ESS
LPA2						
Intercept	-0.01	[-0.08, 0.06]	[-0.19, 0.17]	55.3	1.000	18,490
ST1	**-0.44**	**[-0.49, -0.38]**	**[-0.56, -0.31]**	**100**	**1.000**	**17,555**
SES	-5.14e-03	[-0.04, 0.03]	[-0.09, 0.07]	54.81	1.000	17,784
Weight status	**-0.10**	**[-0.13, -0.07]**	**[-0.17, -0.02]**	**99.5**	**1.000**	**18,071**
Age	**-0.06**	**[-0.08, -0.02]**	**[-0.12, 0.02]**	**93.74**	**1.000**	**18,320**
MVPA2						
Intercept	**0.07**	**[0.02, 0.12]**	**[-0.04, 0.19]**	**88.59**	**1.000**	**17,800**
ST1	**-0.19**	**[-0.25, -0.14]**	**[-0.33, -0.06]**	**99.60**	**1.000**	**18,188**
SES	5.23e-03	[-0.03, 0.04]	[-0.07, 0.08]	55.14	1.000	18,117
weight status	-0.03	[-0.06, 0.01]	[-0.10, 0.05]	77.35	1.000	18,099
age	**-0.02**	**[-0.10, -0.04]**	**[-0.14, 0.00]**	**97.64**	**1.000**	**17,054**

Environment was included as a confounder

Abbreviations: LPA2 LPA in the afternoon, *MVPA2* MVPA in the afternoon, *ST1* ST in the morning, *Pd (%)* Probability of direction of the sign (±), *Rhat* Scale Reduction Factor of the MCMC simulation, *ESS* Effective Sample Size of the MCMC simulation

Table 4 Associations on group level between PA levels in the afternoon and ST in the morning and sociodemographic variables

Parameter (SD's)	Median	60% HDI	95% HDI	Pd (%)	Rhat	ESS
ID level						
LPA2_Intercept	**0.34**	**[0.31, 0.38]**	**[0.26, 0.42]**	**100**	**1.000**	**15,511**
LPA2_ST1	0.09	[0.00, 0.11]	[0.00, 0.21]	100	1.000	11,894
LPA2_SES	0.05	[0.00, 0.06]	[0.00, 0.14]	100	1.000	14,819
LPA2_weight status	0.04	[0.00, 0.13]	[0.00, 0.13]	100	1.000	15,641
LPA2_age	0.06	[0.00, 0.07]	[0.00, 0.14]	100	1.000	15,869
MVPA2_Intercept	**0.37**	**[0.34, 0.41]**	**[0.29, 0.45]**	**100**	**1.000**	**16,618**
MVPA2_ST1	0.06	[0.00, 0.07]	[0.00, 0.17]	100	1.000	14,183
MVPA2_SES	0.06	[0.00, 0.07]	[0.00, 0.16]	100	1.001	13,883
MVPA2_weight status	0.05	[0.00, 0.07]	[0.00, 0.16]	100	1.000	15,555
MVPA2_age	0.04	[0.00, 0.05]	[0.00, 0.12]	100	1.000	16,969
Class Level						
LPA2_Intercept	0.08	[0.00, 0.10]	[0.00, 0.22]	100	1.000	15,375
LPA2_ST1	**0.10**	**[0.03, 0.14]**	**[0.00, 0.22]**	**100**	**1.000**	**17,143**
MVPA2_Intercept	0.07	[0.00, 0.08]	[0.00, 0.18]	100	1.000	17,553
MVPA2_ST1	0.06	[0.00, 0.07]	[0.00, 0.18]	100	1.000	17,348
School level						
LPA2_Intercept	**0.25**	**[0.17, 0.32]**	**[0.09, 0.47]**	**100**	**1.000**	**16,303**
LPA2_ST1	0.10	[0.00, 0.13]	[0.00, 0.25]	100	1.000	16,917
MVPA2_Intercept	0.07	[0.00, 0.09]	[0.00, 0.21]	100	1.000	17,137
MVPA2_ST1	**0.15**	**[0.08, 0.23]**	**[0.00, 0.32]**	**100**	**1.000**	**16,984**

Environment was included as a confounder

Abbreviations: LPA2 LPA in the afternoon, *MVPA2* MVPA in the afternoon, *ST1* ST in the morning, *Pd (%)* Probability of direction of the sign (±), *Rhat* Scale Reduction Factor of the MCMC simulation, *ESS* Effective Sample Size of the MCMC simulation

small negative association was seen between age and LPA in the afternoon (β = -0.06; 60% HDI = [-0.08, -0.02]). MVPA levels in the afternoon were also negatively associated with a medium effect size of ST in the morning (β = -0.19; 95% HDI = [-0.33, -0.06]). Moreover, a small negative association between MVPA in the afternoon and age (β = -0.02; 60% HDI = [-0.10, -0.04]) is shown in the 60% HDI.

Besides the fixed effects, we investigated associations on different group levels (Table 4). On the individual identification **(ID) level,** the intercept in the LPA2-model indicated significant differences between the individual girls in the afternoon (*SD* = 0.34, 95% HDI = [0.26, 0.42]). The direction of the association between ST in the morning time and LPA in the afternoon was not significantly different between the girls (*SD* = 0.09, 95% HDI = [0.00, 0.21]). Furthermore, the direction of the slopes of SES, weight status and age did not significantly vary between them.

Regarding MVPA levels in the afternoon, a significant difference between the girls on the ID level (*SD* = 0.37, 95% HDI = [0.29, 0.45]) was indicated by the large standard deviation of the intercept (MVPA2_Intercept). No differences between the girls concerning the association between ST in the morning and MVPA levels in the afternoon were indicated (*SD* = 0.06, 95% HDI = [0.00, 0.17]).

Regarding differences on the **class cluster-level** related to LPA and MVPA behaviour in the afternoon, there was only a small trend of significant differences in the association between ST in the morning and LPA in the afternoon (*SD* = 0.10, 60% HDI = [0.03, 0.14]).

However, on the **school cluster-level**, girls differed in their LPA in the afternoon (*SD* = 0.25, 95% HDI = [0.07, 0.55]). Related to the association between ST in the morning and MVPA behaviour in the afternoon, the 60% HDI ([0.09, 0.47]) indicated a trend of difference between the girls according to school level.

Weekday vs. weekend

The associations between ST on weekdays and PA on weekends were also assessed.

The model revealed a medium to large sized negative association between ST on weekdays and LPA (β = -0.49; 90% HDI = [-0.60, -0.52]) as well as MVPA levels (β = -0.39; 90% HDI = [-0.53, -0.12]) on weekend days. Additionally, some trends can be seen: for example, weight status and age revealed negative associations with LPA on weekend days (β = -0.09; β = -0.02). Moreover, for MVPA levels on weekend days, SES tended to have a positive association (β = 0.04; 60% HDI = [0.01, 0.08]) (see Table 5).

Besides the fixed effects for all observations of LPA and MVPA on weekends, random effects on the ID, school and class levels were also investigated (Table 6).

On the **ID level**, LPA as well as MVPA on weekend days differed significantly between the girls (LPA *SD* = 0.56; 90% HDI = [0.43, 0.68], MVPA *SD* = 0.38; 90% HDI = [0.26, 0.49]), as did the direction of slope-parameters of ST on weekdays on LPA on weekend days (*SD* = 0.31; 90% HDI = [0.12, 0.46]).

This can also be seen on the **class cluster-level.** Additionally, the ST on weekdays slope concerning weekends' MVPA tended to vary across the girls (*SD* = 0.14; 60% HDI = [0.07, 0.20]).

On the school cluster level, the standard deviation of the slope parameters indicated significant differences in MVPA levels on weekend days between the girls at different schools (*SD* = 0.33; 90% HDI = [0.13, 0.55]). Differences in LPA levels on weekends were only significant at 60% HDI (*SD* = 0.14; 60% HDI = [0.04, 0.20]), thus, indicating a trend. Regarding the slope of ST on weekdays concerning MVPA on weekend days, a variation between the girls on a school level can be seen (*SD* = 0.20; 90% HDI = [0.01, 0.36]).

Table 5 Associations on an observation level between PA levels on weekends and ST on weekdays and sociodemographic variables

Parameter	Median	60% HDI	90% HDI	Pd (%)	Rhat	ESS
LPAWknd						
Intercept	-0.05	[-0.11, 0.01]	[-0.17, 0.08]	74.67	1.000	7652
STWkdy	**-0.49**	**[-0.54, -0.41]**	**[-0.60, -0.52]**	**100**	**1.000**	**6149**
SES	4.99e-3	[-0.04, 0.03]	[-0.07, 0.06]	56.11	1.001	5713
Weight status	**-0.09**	**[-0.10, -0.03]**	**[-0.13, 0.01]**	**93.71**	**1.000**	**4398**
Age	**-0.02**	**[-0.08, -0.01]**	**[-0.11, 0.03]**	**87.04**	**1.000**	**4657**
MVPAWknd						
Intercept	0.07	[-0.03, 0.16]	[-0.12, 0.26]	73.22	1.000	9415
STWkdy	**-0.39**	**[-0.46, -0.31]**	**[-0.53, -0.24]**	**99.99**	**1.000**	**9726**
SES	0.04	[0.01, 0.08]	[-0.03, 0.12]	84.44	1.000	9655
Weight status	-0.02	[-0.06, 0.02]	[-0.09, 0.06]	64.94	1.000	8610
Age	-0.02	[-0.05, 0.02]	[-0.09, 0.05]	65.28	1.000	8660

Environment was included as a confounder

Abbreviations: LPAWknd LPA on weekend, *MVPAWknd* MVPA on weekend, *STWkdy* ST on weekday, *Pd (%)* Probability of direction of the sign (±), *Rhat* Scale Reduction Factor of the MCMC simulation, *ESS* Effective Sample Size of the MCMC simulation

Table 6 Associations on group level between PA levels on weekends and ST on weekdays and sociodemographic variables

Parameter (SD's)	Median	60% HDI	90% HDI	Pd (%)	Rhat	ESS
ID level						
LPAWknd_Intercept	**0.56**	**[0.50, 0.63]**	**[0.43, 0.68]**	**100**	**1.012**	**230**
LPAWknd_STWkdy	**0.31**	**[0.24, 0.40]**	**[0.12, 0.46]**	**100**	**1.003**	**1187**
MVPAWknd_intercept	**0.38**	**[0.32, 0.44]**	**[0.26, 0.49]**	**100**	**1.000**	**2824**
MVPAWknd_STWkdy	0.12	[0.00, 0.14]	[0.00, 0.24]	100	1.000	10,181
Class level						
LPAWknd_Intercept	**0.19**	**[0.12, 0.26]**	**[0.05, 0.33]**	**100**	**1.000**	**3607**
LPAWknd_STWkdy	**0.12**	**[0.13, 0.24]**	**[0.06, 0.31]**	**100**	**1.000**	**5254**
MVPAWknd_Intercept	**0.20**	**[0.12, 0.26]**	**[0.04, 0.34]**	**100**	**1.000**	**6120**
MVPAWknd_STWkdy	**0.14**	**[0.07, 0.20]**	**[0.00, 0.25]**	**100**	**1.000**	**6132**
School level						
LPAWknd_Intercept	0.14	[0.04, 0.20]	[0.00, 0.28]	100	1.000	3901
LPAWknd_STWkdy	0.09	[0.00, 0.11]	[0.00, 0.21]	100	1.000	4243
MVPAWknd_Intercept	**0.33**	**[0.22, 0.41]**	**[0.13, 0.55]**	**100**	**1.000**	**7778**
MVPAWknd_ST1	**0.20**	**[0.12, 0.29]**	**[0.01, 0.36]**	**100**	**1.000**	**6822**

Environment was included as a confounder

Abbreviations: LPAWknd LPA on weekend, *MVPAWknd* MVPA on weekend, *STWkdy* ST on weekday, *Pd (%)* Probability of direction of the sign (±), *Rhat* Scale Reduction Factor of the MCMC simulation, *ESS* Effective Sample Size of the MCMC simulation

Discussion

The aim of the present study was to investigate, with respect to (pre)adolescent girls in Germany, whether ST in the morning is compensated by PA in the afternoon and, whether ST on weekdays is compensated by PA behaviour on weekends. Additionally, we examined whether these relationships are moderated by the SES, age or weight status of the (pre)adolescent girls.

By applying a within-person design, compensation analysis related to afternoon and weekend PA was conducted for every single girl in our study. Our findings reveal compensatory behaviour in the afternoon period in 60.4% of the observation points across all 370 girls who participated in this study. For a better understanding, we would like to review the meaning of observation points ones more. These refer to the fact that one girl can produce values on several days in the morning and in the afternoon over a period of seven days. Thus, girls could have multiple observation points. Related to weekend PA, 59.2% of the (pre)adolescent girls indicated compensatory behaviour. We conducted differentiated analyses and found in our sample that during weekdays 614 observation points in girls indicated lower ST in the morning compared to afternoon. All these showed a negative compensation with lower PA in the afternoon. Similar results can be seen regarding weekend compensation: all girls ($N=199$) with lower ST levels during the week compared to the weekend showed lower PA levels on the weekend. Thus, all these girls compensated negatively. Nevertheless, our data indicate that more ST in the morning or on weekdays is compensated positively by more PA in the afternoon or on weekends, even if the number of girls doing so in the present sample was small. In the afternoon, only 14.2% (75 of 528) of the observation points with more ST levels in the morning showed an increase of PA levels in the afternoon, and on weekends less than 12% compensated positively for more ST during the week with more PA on the weekend (20 of 171 girls). Interestingly, the number of girls who did not compensate, is represented only by those girls who had high ST levels in the morning/on weekdays and did not increase their PA levels in the afternoons/on weekends. Thus, they accumulate throughout the day and entire week low PA levels. This result can also be seen regarding the negative association between ST levels and PA levels (see Tables 3 and 5).

The latest reviews summarising existing literature related to compensatory behaviour in children and adolescents reveal similar results [38, 39]. In the present study, in the afternoons as well as on weekends, 53.8% of observation points indicated negative compensatory behaviour and our review [38] also indicates negative compensatory behaviour in half of the studies that focused on daily PA behaviour [40–46]. The latest review by Swelam, Verswijveren [39] analysing youths and adults compensatory behaviour indicates compensatory behaviour in one-third of the 5 to 18-years-olds, thereby confirming the inconsistent results of the present study.

In addition to the negative compensatory behaviour in the present sample, our data indicate positive compensatory behaviour in a few girls. Until now, only two studies revealed positive compensatory behaviour in children and adolescents: Tudor-Locke, Lee [29] reported a positive compensation in girls with lower PA levels in school and increased PA levels out of school. Thus, total PA related to the entire day did not differ between girls with higher and lower in school PA in this study. Another study on German children indicated higher MVPA levels than usual the day after higher than usual ST levels [48]. Interestingly, positive compensation in differentiated analyses was seen more frequently in the afternoon compared to weekend days (14.2% vs. 11.7%). This could be explained by generally higher PA levels during the week compared to weekends [40, 72, 73]. Furthermore, literature suggests that weekends were not used for PA by children and adolescents [73], even if there was enough time, because children and adolescents did not go to school. In addition, training times for sports clubs more frequently occur during the week in the afternoon/evening when schools offer opportunities to be active (e.g., active commuting to school, extracurricular PA, PE) [74–76].

In this context, we would like to highlight the differentiation of positive and negative compensation in our study, as we are the first to do so. Due to our descriptive analysis of compensation we were able to determine for each girl/observation point the individual PA behaviour. This makes it possible to determine and differentiate between positive or negative compensatory behaviour in girls, or the absence thereof. Most of the existing studies analysed compensation across the mean values of the group and thus only obtained one value for each timespan [36, 77–80]. Nigg, Burchartz [48] also take the individual mean values of every individual into account for compensation analysis; nevertheless, the result of the multilevel analysis indicated one mean value under consideration for all the participants' individual means.

Furthermore, related to our additional multilevel analysis, compensatory behaviour differs between the girls. Nevertheless, these differences in the compensatory behaviour were not related to any of the sociodemographic variables we included, such as SES, age or weight status. Thus, we assume that it depends on individual or social factors (e.g. intrinsic motivation as well as social support). Furthermore, Swelam, Verswijveren [39] also stated individual reasons for compensation like fatigue, time constraints, lack of motivation, drive to be inactive, fear of overexertion, and autonomous motivation. These results are confirmed by the Eurobarometer Study [81], which investigated, among other things, the barriers for engaging in PA. It was found that especially for younger adolescent girls barriers to PA are a lack of time followed by a lack of motivation and interest [81].

As we conclude, to avoid a negative compensation following more PA in the morning/on weekdays, it is important to support (pre)adolescents in their active lifestyle after school and especially on weekends. Therefore, it seems important to develop strategies to promote PA levels after school and on weekends, and these should also focus on changing the attitude and mind of the adolescents related to PA [26, 82, 83].

The importance of the schools as a promoter of PA is also confirmed when regarding our results on the class and school levels. Especially on a class level, differences can be seen between the girls regarding the association between ST in the morning/on weekdays and LPA in the afternoon/on weekend days. This means, that compensation occurs depending on class affiliation. MVPA levels and compensatory behaviour with MVPA were observed with regard to school level. Unfortunately, we do not have further information about the school profiles or timetables of the classes, which makes it difficult to interpret these findings. However, these factors seem to be relevant moderators of compensatory behaviour. Further studies should focus on differences between class and school levels by taking school profiles and timetables into account.

Lastly, we would like to focus on the timeframe of compensatory behaviour. Existing reviews indicate inconsistent results related to the timeframe of compensation. Overall, compensatory behaviour occurs within days, between days as well as over (several) weeks [27, 38, 39]. Gomersall, Rowlands [27] hypothesised that the timeframe for compensation is unlikely to be day to day. However, our review revealed that most included studies investigating PA behaviour within days showed that half indicated compensation [38] as it can also be seen in the current study. On the other hand, the review of Swelam, Verswijveren [39] found as much compensatory behaviour within as between days (approx. 25%). Nevertheless, compensatory behaviour between weekdays and weekends was scarcely investigated [84]. Thus, our data expanded the current state of research related to weekend compensation and demonstrated compensatory behaviour in more than half of the girls (53.8%).

In summary, our findings reveal that half of the female sixth graders in our study showed a positive or negative compensatory behaviour. Thus, we can neither confirm nor reject the ActivityStat Hypothesis, stating that an increase of PA in one timespan is compensated by a decrease of PA in another timespan [27]. Overall, the results indicate that PA behaviour in the afternoon or on the weekends are predominantly individual and differ greatly between the girls. In addition, PA behaviour in our study was not associated with age, weight status or SES. Nevertheless, further variables regarding SES like possessing a car and/or bicycle should be considered and could be associated with compensatory behaviour. In addition, further compensation studies should focus on individual variables like social support as the literature has suggested differences in PA levels depending on social support [85]. Furthermore, intervention or health programmes targeting on a positive attitude towards PA should be implemented to highlight the importance of sufficient PA for health [26, 82].

Strengths and limitations

The major strength of this study is its detailed insight into device-based assessed PA and ST behaviour during weekdays (morning, afternoon) as well as on weekends concerning (pre)adolescent girls, a high-risk population. This allows for conclusions about compensatory behaviour and potential moderators. This study expands the current research of the PA and ST of students due to its detailed analysis of a large sample size, which establishes a foundation for further investigations. Furthermore, we investigated and reported the compensatory behaviour of each individual and were thus able to differentiate between positive, negative and no compensation within the sample. Existing studies have mainly analysed compensation with mean PA values and this study is the first to investigate the compensatory behaviour of girls on different levels (ID, school, and class) and under the consideration of different moderators (age, weight status, SES).

Nevertheless, this study has several limitations. Further factors like seasonal and meteorological variability mediating PA and ST levels were not considered in the analysis. Furthermore, we did not analyse different segments during the school day to acquire more information about PA behaviour during school hours as applied to other studies [86]. Lastly, we do not have any information about the school profile and/or the timetables of the students which makes it difficult to interpret our findings related to school and class level effects. In this context, it would generally be helpful to give participants, in addition to the accelerometers, a diary in order to gain more information about their behaviour. Besides the school profile, the school district SES could be included in further studies, as an existing study revealed an association between the socioeconomic circumstances of the area the children lived in and health development [87].

Conclusion

The present study investigated compensatory behaviour and moderating variables in a sample of sixth-grade girls ($N=370$). Our results indicated compensatory behaviour in about 60% of all observation points, both in the afternoon and, on weekends. However, concerning this behaviour, only a few girls revealed a positive compensation by increasing their PA behaviour after a high amount of ST. On the other hand, all girls with low ST levels in the morning or on weekdays, compensated for this behaviour with lower PA levels in the afternoon or on weekend days. This behaviour directly prompts for action to maintain a high PA level throughout the entire day/week. Inferential analysis confirmed our results and implicated that there were intra-individual differences in the occurrence of a compensatory behaviour. However, relevant moderators explaining intra-individual differences were not identified. In the future, to prevent negative compensation, school-based interventions that have the potential to provide opportunities to be active, should not neglect (pre)adolescents' out of school behaviour. Theoretical models [88] and empirical findings [89] indicate that PA promotion programmes are more effective if they address more than one level of influence (e.g., school and family). Furthermore, one important point could be to highlight the importance of PA for health and motivate them to stay active throughout the whole day.

Abbreviations

BMI: Body Mass Index; CPB: Compensatory physical behaviour; Cpm: Counts per minute; EE: Energy expenditure; ESS: Effective Sample Size of the MCMC simulation; HDI: High density interval; HISEI: Higher International Socioeconomic Index of occupational status; ICC: Intra-class correlation coefficient; ISEI: International Socioeconomic Index of occupational status; LPA: Light physical activity; MCMC: Markov chain Monte Carlo simulation; MVPA: Moderate-to-vigorous physical activity; PA: Physical activity; Pd (%): Probability of direction of the sign (±); PE: Physical Education; Rhat: Scale Reduction Factor for MCMC simulation; SES: Socioeconomic status; ST: Sedentary time; WHO: World Health Organization.

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Authors' contributions

Conceptualisation: F.B., U.D., D.J.S., A.K.R.; Methodology: F.B., U.D., D.J.S.; Formal Analysis: F.B., U.D.; Preparing Figures and Tables: F.B.; Writing – original draft: F.B.; Writing – review & editing: F.B., U.D., D.J.S.; Y.D., A.K.R.; Project administration: Y.D.; Supervision: A.K.R. The author(s) read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The study was approved by the Ethics Committee of the Technical University of Munich (protocol code 155 / 16S) and was in accordance with the 1964 Declaration of Helsinki. All participants as well as one of their parents provided written informed consent for study participation.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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Summary

This study investigated compensatory behavior in (pre)adolescent girls with the focus on timespan of potential compensatory responses and moderating effects of age, weight status and SES. Our findings based on the CReActivity data (collected with accelerometers) could neither confirm nor reject the ActivityStat hypothesis. Descriptive analysis revealed rather constant compensatory behavior of about 60% for after-school days and weekends over all observation points. However, regarding all girls, compensation was predominantly negative connotated: differentiated analysis indicated that all girls with low sedentary time levels in the morning or on weekdays, compensated for this behavior with lower PA levels in the afternoon or on weekends. Interestingly, PA compensatory behavior is not associated with age, weight status or SES. In contrast, data indicated great variability across the girls, and thus, it seems that compensation depends on other, more individual factors.

Consequences

Summarizing the findings from the previous compensation articles, inconclusive results concerning activity compensation in children and adolescents could be identified. Even if device-based activity monitoring is essential in providing quantitative data and assessing compensatory behavior, it seems not to be sufficient enough to holistically understand activity compensation in children and adolescents. Especially, to provide insights into the behavioral context of activity compensation as well as perception and influencing factors, subjective measurement tools can be helpful to gain a deeper and holistic understanding of activity compensation. Thus, the following section will focus on subjective measurements and their usefulness in measuring activity behaviors, respectively activity compensation.

4.2 Activity Compensation Based on Subjective Measurement Methods

Overall, there exists a wide range of subjective measurement methods like surveys, diaries, and interviews that can be used to assess PA behavior in children and adolescents. These methods have numerous advantages, for example low costs, low participant burden and ease of administration. Furthermore, the establishment of mode, setting, and/or context of which activity takes place, along with the perception associated with activity behavior, can be assessed using specific type of subjective measurement (Corder et al., 2008; Trost et al., 2000). Precise advantages for different tools will be discussed later. Nevertheless, subjective measurements are influenced by a number of factors which may hinder their accuracy in measuring activity in children (Corder et al., 2008). As an illustration, subjective instruments designed to measure activity rely on an individual's capacity to retrospectively and precisely recall PA (Loprinzi & Cardinal, 2011), leading to an oftentimes low accuracy and overestimation of PA levels (Prince et al., 2008; Sallis & Saelens, 2000). Further challenges may be the perception and bias of the participant, proxy reporter, or investigator (e.g., recall, social desirability, investigator bias, etc.) (Corder et al., 2008). In addition, compared to sensors that can simply be worn on the body, some subjective tools like diaries have high level of participant expenditure (Dollman et al., 2009).

As for the present thesis, especially for Manuscript E, two types of subjective methods are highly relevant, and these will be explained in more detail in the following paragraphs.

Interviews

Interviews are an effective data collection method, especially for movement behaviors as they allow for insights into the context of activity and situations that may not be easily identifiable from tools such as accelerometers or survey data alone (Bowling, 2009; Crone & Lonzano-Sufrazegui, 2019; Hansen, 2020). One of the most important advantages is that interviews can uncover reasons for and/or perceptions behind individual behavior, as opposed to group behavior (Gibson, 2012). This can be achieved from multiple perspectives (e.g., parents and children) and also can help to clarify any ambiguities or misconceptions that may arise in other data collection methods (Crone & Lonzano-Sufrazegui, 2019). The highly personal nature of the interaction allows for responses to be articulated in children's own language and thought patterns (Freeman & Mathison, 2009; Gibson, 2012), making it particularly useful for understanding the context and reasoning behind specific behaviors. Consequently, researchers must be trained and prepared to respond with sensitivity, appropriateness, and non-judgment to elicit unbiased responses (Gibson, 2012). Another advantage of interviews is their flexibility, providing researchers the opportunity to gather crucial information efficiently (Freeman & Mathison, 2009). Interviews do not demand participant literacy, although a certain level of language proficiency is required (Bowling, 2009). Notably, experts in qualitative data collection assert that children as young as seven can offer thoughtful and informative responses in interviews (Gibson, 2012). However, despite these advantages, interviews can be costly due to the time needed for conducting, transcribing, and analyzing data. Additionally, the outcomes can heavily depend on the skill and previous training of the interviewer, especially considering the diverse development stages of children and adolescents (Bowling, 2009; Gibson, 2012).

Diary

Diaries are more and more used to assess PA behavior in children and adolescents, especially in large cohort studies (Ndahimana & Kim, 2017). Diaries can be used to assess the type, duration and subjective intensity as well as the timepoint of the activity and further relevant information like weather, mood, accompanionship. Furthermore, with increasing digitalization, activity diaries are digitalized and can be used on the own smartphone. Various mobile applications allow to shape the activity diary program exactly towards the research focus of the respective, in particular the setting of activity (e.g., ClueTec GmbH). Costs of smartphone-based diaries are quite low since no material costs and personnel resources are needed. With a good preparation, contact time with the subjects approaches close to zero, while digitization automatically prevents most data errors and allows data to be prepared for evaluation right away (Beneke, 2008; Ndahimana & Kim, 2017). Additionally, since PA diaries require participants to record performed activities in real time, they minimize the memory bias in case they are completed on time. However, the burden to participants is higher compared to PA questionnaires and if there is a delay in recording the activities, there may also be a memory bias and reactivity (Ndahimana & Kim, 2017). However, there are also limitations in the usage of activity diaries to assess PA levels. First of all, diaries have high participants expenditure as they have to track their activity (plus questions referring the activity) over a period of time (Dollman et al., 2009). Furthermore, depending on the cognitive ability of the participants, accuracy could be low due to comprehension problems or memory problems if activity is not recorded in real time. Lastly, social desirability may have an influence on the accuracy of the tracked activities (Rudolf, 2020).

Chapter 4.1 described device-based measurement tools and their advantages as well as disadvantages and first attempts to capture compensatory behavior in children and adolescents. Within Manuscript C and D, we focused on activity compensation using device-based approaches allowing the quantification of activity that results in PA and SB estimates that exhibit high reproducibility. However, as results regarding activity compensation in children and adolescents were inconclusive, these approaches seem not to be sufficient enough to assess activity compensation in children and adolescents. Thus, by using subjective measurement tools, more information about the mode, setting, and/or context of which activity takes place, along with the perception associated with activity behavior, can be drawn. These methods could then help to understand compensation and the underlying mechanisms as well as influencing factors in a holistic way. Due to the mentioned advantages of subjective measurement methods, we focused in the following chapter on activity compensation by using subjective tools.

4.2.1 Manuscript E: Compensatory Behavior of Physical Activity in Adolescents – A Qualitative Analysis of the Underlying Mechanisms and Influencing Factors

Beck, F., Swelam, B. A., Dettweiler, U., Krieger, C., & Reimers, A. K. (2024). Compensatory behavior of physical activity in adolescents – a qualitative analysis of the underlying mechanisms and influencing factors. *BMC Public Health, 24*(1), 158. https://doi.org/10.1186/s12889-023-17519-1

Introduction

Within the systematic review (Beck et al., 2022b) as well as the empirical article (Beck et al., 2022a) that focused both on activity compensation using device-based measurement methods, inconclusive results were revealed. Especially, analysis could not identify consistent compensatory responses and no association between any sociodemographic variable and compensation was found. Rather it is suggested that compensation is a quite individual behavior. To address this concern, subjective measurement tools are a good option to investigate movement behaviors as they allow for insights into the context of activity and situations. Thus, we conducted a qualitative study using subjective measurement tools to gain a deeper understanding of the underlying individual mechanisms. The qualitative study consists of three parts: a habitual weekly schedule, an activity diary over one week and a semi-structured interview that allows an in-depth analysis of the ActivityStat hypothesis, including affecting variables. An existing study from Australia conducted interviews with elementary school children and identified several variables like environmental, physiological and social factors that could explain compensatory behavior (Swelam et al., 2023b). Nevertheless, this study was conducted in Australia and with elementary school children. Besides the potential factors influencing compensatory behavior, there is also a lack of conclusive information about the timespan of compensation. Furthermore, none of the existing studies focused on the amount of PA that is compensated and/or compensates the deviation of PA. Thus, the aim of the present study was to investigate whether adolescents compensate for increases or decreases in their habitual PA within-day/between-days and whether this is directly perceived. Furthermore, we wanted to identify the influential mechanisms or factors on compensatory behavior.

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RESEARCH

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Compensatory behavior of physical activity in adolescents – a qualitative analysis of the underlying mechanisms and influencing factors

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Abstract

Introduction Compensatory behavior of physical activity (PA) based on the ActivityStat hypothesis in adolescents is scarcely investigated, and existing studies showed inconclusive results. Understanding the compensatory behavior in a holistic way is important as this can help to improve intervention outcomes and thus, increase the PA levels in adolescents. Thus, the aim of the present study is to investigate the occurrence, direction, timeframe, and ratio of habitual activity compensation in adolescents. Furthermore, we want to identify the awareness of compensation and factors that influence compensatory behavior.

Methods The present qualitative study used a mixed methods crossover analysis design. Participants ($N=15$, 8 boys and 7 girls) were adolescents aged 11–15 years (mean age 13.04 ± 1.28). They provided a habitual weekly schedule with habitual/regular activities and their intensity. Participants then kept an activity diary over one week to capture their actual behavior. After that, data were compared and deviations $> \pm 20\%$ were considered as compensation opportunities. On this basis, deviations were descriptively analyzed for compensatory behavior and were coded as positive and negative compensatory behavior. Further, for each compensation, the ratio of compensation (*MET-minutes of the compensating activity/MET-minutes of the activity that was compensated*) was calculated. Additionally, interviews were conducted to explore perceptions and influencing factors for (no) compensation.

Results Overall, 198 compensation opportunities were identified with deviations greater $\pm 20\%$. Of these, 109 opportunities were compensated overall (69 within-day, 40 between-day). Negative compensation took place in 57 opportunities and 52 opportunities were compensated positively. Most of the deviations were overcompensated (compensation/deviation $> 100\%$). About half of the adolescents ($N=8$) were not aware about their compensatory behavior, and only one boy was aware of all his compensatory behavior. The most mentioned influence for positive compensation were social support by friends and good weather. As influencing factors for negative compensation, tiredness as well as no need for movement were mentioned predominantly. No negative compensation occurred because adolescents wanted to stick to their routines or participated in hedonistic activities.

Discussion Summarizing the findings, the present study delivered new insights into the field of compensatory behavior in adolescents. Nevertheless, compensatory behavior was not consistently observed regarding the occurrence of compensation, direction, timeframe and ratio. However, social support appears to be an important factor

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to compensate positively or to avoid a negative compensatory behavior. Further, it seems to be helpful to support individuals in their search for hedonistic activities as well as in the establishment of routines.

Keywords Physical activity, Compensation, Youths, Qualitative

Introduction

Physical activity (PA) is associated with several health benefits in children and adolescents [1–5] like improved physical fitness [6–8], a reduction in the risk of obesity, and improvements in cardiovascular and cardiometabolic health [1, 4, 9]. However, children and adolescents in many regions worldwide do not meet the WHO recommendations for PA [10–13]. In addition, with increasing age, the prevalence of compliance to the WHO PA guidelines decreases [14–16]. Despite numerous efforts to promote PA among children across different settings, including schools, the family environment or local community settings, the effectiveness in the short and long term has widely varied and is not sufficient [17, 18].

To successfully harness the health effects of PA (within interventions), it is important to fully understand the determinants. In this regard, some studies have focused on potential biological influences of PA, specifically the potential effects of intrinsic biological control on regular activity [19, 20]. This issue was highlighted with Rowland's seminal ActivityStat hypothesis paper [20], which has since gained prominence in the literature. This hypothesis focuses on the potential effect of intrinsic biological control that may underpin PA and energy expenditure (EE). In particular, the ActivityStat hypothesis posits that an imposed increase or decrease in PA in one domain/timespan might induce a compensatory change in the opposite direction in another domain/timespan in order to maintain a stable level of PA or EE over the time [21]. However, until now, reviews on compensatory behavior studies have found inconsistent results regarding the support for the ActivityStat hypothesis [21–23].

Previous research has suggested that perceptions of PA can be an important indicator of activity behavior [24, 25]. Therefore, understanding adolescents' perceptions of their activity behavior may be important in understanding the causes of their compensatory behavior. Specifically, this may provide further insights into the malleability of the ActivityStat hypothesis [26–28], as well as an understanding of whether external factors (e.g., environmental, interpersonal, etc.) may influence compensatory responses. Until now, few studies have examined perceptions of compensation and/or mechanisms of compensation (i.e., whether adolescents perceive that they compensate their activity and if so, what factors influence this) [29, 30]. Furthermore, relatively little research has been done on adolescents [29]. However, this was not a purpose-designed study to explore the perceptions of compensation in this age group. A previous study examining perceptions and mechanisms of compensation in primary school children identified several influences on compensation, as well as an awareness of within-day PA compensation [31]. Whilst this study identified effects of environmental (e.g., home structure), interpersonal (e.g., co-participation), psychological, and physiological factors, it does not focus on the PA amount of deviation from the habitual PA that leads to a compensatory behavior as well as the amount of compensatory PA. In addition, this study occurred in pre-adolescent participants.

Therefore, the aim of the present study was to investigate whether adolescents compensate for increases or decreases in their habitual PA within-day/between-days and whether they perceive this directly. Furthermore, we wanted to identify the mechanisms and factors that influence compensatory behavior.

Methods

Study design

The present qualitative study used a mixed methods crossover analysis design [32]. The study was approved by the local Ethics Committee of the Friedrich- Alexander-Universität Erlangen-Nürnberg (Ref. No. 23–31-S) and was in accordance with the 1964 Declaration of Helsinki. All participants and their legal guardians provided written informed consent for study participation.

Participants

Adolescents aged 11–15 years and living in Germany, were recruited via personal contacts, various youth institutions as well as sports clubs and other leisure time instances in the region of Erlangen (Bavaria). These participants were recruited using theoretical sampling methods [33], and were selected in accordance with our proposed analysis processes and theoretical underpinnings. This included ensuring the samples contain diversity with respect to socioeconomic status, migration background, sex/gender and environmental conditions (e.g., urban and rural living locations). In more detail, we tried to find an equal amount of boys and girls for each categorie (sex/gender, age, migration background, living area, and school type). Our final sample consisted of 15 adolescents. Adolecents could not be part of the study if they had a physical disability or if they didn't have a smartphone. All participants received 10 Euro as an incentive.

Data collection

First of all, sociodemographic data, like age, gender, educational level, and residential area, was collected from both adolescents and their parents via a short questionnaire sent per e-mail. Data collection took place in spring 2023 and had three parts. First, participants were asked to fill a schedule with all of their habitual/typical physical activities in a given week via a plain document. Within the information letter and the example of a weekly schedule (Additonal file 1) participants received additional information for the weekly schedule. Examples of activities were provided to increase clarity. Nevertheless, if adolescents needed help to fill out the habitual schedule, they could reach out to our research team or ask their parents. The following week, participants were asked to track their activities via a smartphone-based diary app (ClueTec GmbH; https://www.cluetec.de). To use the diary, adolescents received a QR-code that made an installation of the programmed diary available. To minimize recall bias, adolescents were instructed to track their activities ideally immediately after the activity, however, if this was not possible, then always as soon as possible. Following the completion of the weekly schedule and the movement diary by participants, the research team assessed the schedule and diary for potential compensatory behavior. Then, participants engaged in an online interview via Jitsy-Meet (8×8 Inc.). Interviews were anticipated to take around 30 min to complete, however, a 60 min appointment was scheduled to allow for potential deviations. After giving informed consent and agreeing on an appointment, each participant received an individual link for an online meeting to conduct the interview. Participants were able to complete their interview from any desired place so long as they had a stable internet connection and quiet surrounding. Before the start of the recording, the objective and the interview procedure were explained and participants were reassured of the voluntary nature of their involvement and their right to refuse to answer any questions. After clarifying any questions that participants had, the audio recording device was turned on and the interview began. All participant data was de-identified to ensure anonmyity and participant names were not recorded during interviews.

Measures

Weekly activity schedule (habitual PA)

Participants provided information about their habitual (active and non active) activties within one week. They gave information about the time of the activity, the duration, type and intensity. To ensure participant clarity and understanding, participants received a template containing two examples (Additional file 1).

Smartphone-based activity diary (actual PA)

Participants were asked to track their activities with a smartphone based diary app (ClueTec GmbH). Participants were asked to track each PA they did, and upon recording the activity in the diary, were asked the following questions: What did you do exactly? For how long? How was the intensity (LPA, MPA, VPA)?

Semi-structured interview – interview guideline

The interview guideline was based on the comparison of the weekly activity schedule and the diary (Additional file 2). This allowed for the identification of compensatory behavior. The specific questions that were asked were dependent on whether compensation had occurred or not, with subsequent questions relating to perceptions of compensation, and influencing factors for the compensatory behavior (or not) (e.g., why did you do more/less at time point X and why subsequent less/more than usual at timpoint Y? Did you perceive that you compensate your activity?).

Data analysis

Descriptive analysis of deviation and compensation with weekly activity schedule (habitial PA) and activity diary (actual PA)

To explore compensation, MET-minutes were calculated for each habitual physical activities (derived from the weekly schedule) and actual physical activities (derived from the smartphone diary). Sedentary behavior was not considered in our data analysis that focus on activity compensation. The Youth Compendium of PA [34] was utilised to calculate the MET cost for each activity (if an activity wasn't listed in the Youth Compendium, the MET cost was estimated based on similar activities), then subsequently multiplied by the duration of the activity to determine the MET-minutes for each activity. To determine wether deviation had occurred, the difference between the actual MET-minutes of the diary activity and the habitual MET-minutes of the weekly schedule' activity at the same time period (MET-minutes_actual – MET-minutes_habitual) as well as the percentage of this difference were calculated.

To define opportunities where compensatory behavior could occur, the intra-individual variability was considered. Therefore, to be identified as a possible compensatory opportunity, the difference between habitual MET-minutes in the weekly schedule's activity and actual MET-minutes from the diary's activity at the same time point had to be at least ± 20% different from the habitual

MET-minutes [26, 35] (Additional file 3). Possible compensatory opportunities were then assessed to determine if compensation had occurred (or not) within that same day (within-day) and/or the next day (between-day), and in which 'direction' (i.e., positive or negative compensation). The compensatory definitions have been provided in Table 1.

After identification of compensation in the participants, the ratio of compensation (MET-minutes of the compensating activity /MET-minutes of the activity that was compensated) was calculated and we distinguished between partial compensation (low: 0–49.9%. medium: 50–74.9% and high: 75–99.9%) and overcompensation (≥ 100%) [35].

On overview of data collection and data reduction process can be seen in Fig. 1.

Qualitative data – interviews

Interviews were transcribed verbatim according to DresingPehl [36] using f4transcript (audiotranskription.de). The resulting text files were checked for correctness. For the purpose of this paper, we translated the example quotes from German to English.

Using the transcribed interview text, qualitative content analysis [37–39] was performed in QCAmap (https://www.qcamap.org/ui/en/home) [40]. Due to the category-guided approach, the analyses of the interviews was limited to verbal statements, whilstpara-verbal (e.g., body language, tone, etc.) information was not assessed, as it was deemed irrelevant for the extraction of information with regard to the research question [41]. Initial coding of interviews was based on principles derived from the ActivityStat hypothesis [21, 28] and considerations from previous qualitative studies examining awareness and potential mechanisms of compensation in elementary school children [31] and adults [30]. This analyzing stategy focused on awareness of compensatory behavior, influences for compensation as well as for not compensating. One author (FB) and a trained research assistant student conducted deductive analyses of the transcripts for awareness of compensation ("yes" or "no") and inductive for influencing factors for (no) compensation. The codes were developed and categorized and further discussed with the research team.

Results

Sample characteristics

The mean age of the 15 adolescents (8 boys and 7 girls) was 13.04 ($SD = 1.28$). For the age of 15, we only had one boy and no girl. Overall, about half ($N = 6$; 3 boys and 3 girls) of the participants attended a secondary school (Realschule), whilst the majority ($N = 8$; 4 boys and 4 girls) of remaining participants attended high school (Gymnasium). For middle school, we only included one boy. An imbalance can be seen in the type of residence for rural areas (5 boys and only 1 girl live in rural areas). The majority of the adolescents' parents were born in Germany, with the exception of two participants with either one ($N = 1$) or both ($N = 1$) parents born outside of Germany. Overall, the adolescents accumulated in the diary 661.0 (293.6) MET-minutes per day in the diary, indicating an active sample (moderate PA = 3–6 MET-minutes, vigorous PA > 6 MET-minutes) [42]. Further information can be seen in Table 2.

Data quality

Filling out the habitual weekly schedule took the adolescents around 30 min. For each activity that was tracked in the activity diary, adolescents needed 2–5 min. The weekly schedule contained no time gaps. In the activity diary, only PA was tracked. If there was something missing in the diary, which was supposed to be included, participants were contacted individually and asked if this hadn't taken place or if it just had been forgotten.

Table 1 Definition of compensation related terms

Term	Defintion
Deviation	The difference between the actual MET-minutes of the diary and the habitual MET-minutes of the weekly schedule (MET-minutes_actual – MET-minutes_habitual)
Compensation opportunitiy	Participants had less/more Metabolic equivalent (MET)-minutes activity in the 'actual' week than their 'habitual' week, this was classified as a 'compensation opportunity'
Positive compensation	In the case that participants completed additional non-habitual MET-minutes in the actual week following this change, this was considered 'positive compensation'
Negative compensation	In the case that participants completed less non-habitual MET-minutes in the actual week following this change, this was considered 'negative compensation'
Ratio of compensation	The ration of compensation is calculated by following equation: *MET-minutes of the compensating activity /MET-minutes of the activity that was compensated* Ratio of compensation is distinguished between partial compensation (low: 0–49.9%. medium: 50–74.9% and high: 75–99.9%) and overcompensation (≥ 100%)

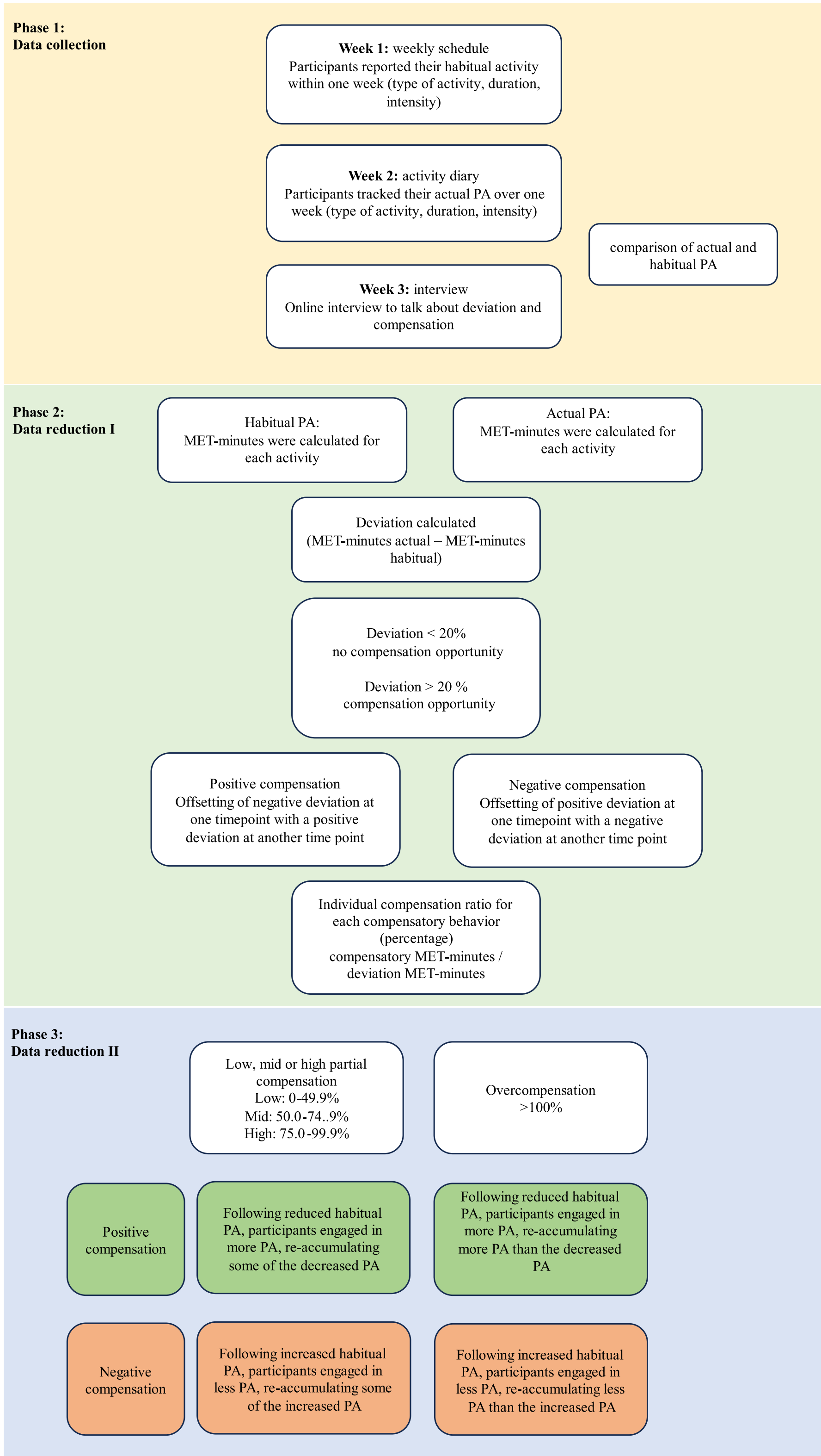

Fig. 1 Data collection and data reduction process

Table 2 Sample description

	Overall	Boys	Girls
Adolescents			
N (%)	15 (100)	8 (53)	7 (47)
boys			
girls			
Age (mean SD)	13.04 (1.28)	12.99 (1.46)	13.10 (1.17)
11 (N, %)	3	2 (66.7)	1 (33.3)
12	4	2 (50.0)	2 (50.0)
13	5	2 (40.0)	3 (60.0)
14	2	1 (50.0)	1 (50.0)
15	1	1 (100)	
School type			
Middle School (Haupt/Mittelschule)	1 (7)	1(12.5)	0
Secondary School (Realschule)	8 (53.3)	4 (50.0)	4 (57.1)
High School (Gymnasium)	6 (40)	3 (37.5)	3 (42.9)
Urbanisation			
City > 100.000 inhabitants	5 (33)	2 (25.0)	3 (42.8)
Medium sized town 20.000–100.000 inhabitants	4 (27)	1 (12.5)	3 (42.8)
Rural area/village	6 (40)	5 (62.5)	1 (14.4)
Migration Background			
None	13 (87)	6 (75.0)	7 (100)
One custodian	1 (7)	1 (12.5)	0
Both custodian	1 (7)	1 (12.5)	0
Activity Level			
Diary MET Min per day (mean; standard deviation)	661.0 (293.6)	796.4 (304.9)	506.3 (183.4)
Range (min – max)	227.3 – 1175.4	389.1 – 1175.4	227.3 – 724.1
Custodians			
Educational Level of custodian 1			
(qualified) middle school degree	4 (26.7)	2(25.0)	2 (28.6)
High school degree	11 (73.3)	6 (65.0)	5 (62.5)
Educational Level of custodian 2			
Finished school without degree	1 (7.1)	1 (12.5)	0
Middle school degree	6 (42.9)	3 (37.5)	3(50.0)
General high school degree	7 (50.0)	4 (50.0)	3 (50.0)
Employment of custodian 1			
Part-time	9 (60.0)	3 (37.5)	6 (85.8)
Full-time	6 (40.0)	5 (62.5)	1 (14.2)
Employment of custodian 2			
Unemployed	1 (6.7)	1 (12.5)	0
Retiree	1 (6.7)	1 ()	0
Part-time	1 (6.7)	1 (12.5)	0
Full-time	11 (79.9)	5 (62.5)	6 (100)

Descriptive compensation analysis

Overall, 198 opportunities were identified where participants had a (positive/negative) ± 20% deviation from the habitual PA (condition/perquisition for compensation). Among these, 114 (57.6%) of possible compensation opportunities occurred in boys, whereas 84 (42.4%) occurred in girls. Compensation occurred n 55.1% ($N = 102$) of the possible compensation opportunities. Boys compensated in 75 out of 114 (64.0%) possible compensation opportunities whereas girls compensated in 34 out of 84 (40.5%) possible compensation opportunities. Positive compensation occurred in 52 of the 198 opportunities (26.3%; boys, $N=41$; girls, $N=11$), whereas negative compensation occurred in 57 opportunities (28.8%; boys, $N=34$; girls, $N=23$).

Positive compensation

To compensate in a positive way, a negative deviation must have preceded, i.e., the actual PA at a given time point t is lower than the habitual PA at this time point. Details about the amount of MET-minutes for deviations and compensation overall, as well as for boys and girls can be seen in Additional file 4. Looking at the ratio of compensation, overall, it ranged between 6% (low partial compensation) and 2068% (overcompensation). In boys and girls, similar tendency can be seen (boys: 6% to 1533%, girls: 7% to 2068%). Figure 2 illustrates the amount of deviation and compensation for each occurred compensation (left) and the associated ratio of compensation (right). In addition, proportion of low, medium, high and overcompensation for negative compensation can be found in Additional file 5.

Lastly, regarding the timeframe, of all [$n=52$] positive compensatory behaviors, 65.4% [$n=34$] occurred within-day, whereas 34.6% occurred between-day (see Additional file 6). Between-day could either refer to successive days like Monday-Tuesday or occur over several day like Monday-Friday. Further, Fig. 2 shows the amounts of MET-minutes. Additional file 4 shows the amounts of MET-minutes for deviation and compensation within and between day. The compensation ratio ranged in boys within-day from 6 to 1533% and between-day the ratio of compensation was 11% to 377%. Ratio of compensation in girls ranged from 58 to 149% within-day and 7% to 2068% between-day.

Negative compensation

In contrast, positive deviation leads to negative compensatory behavior. The amount of deviation and compensation can be seen in Additional file 4 as well as in Fig. 3. The ratio of compensation ranged between 4% (low partial compensation) and 2173% (overcompensation) (see

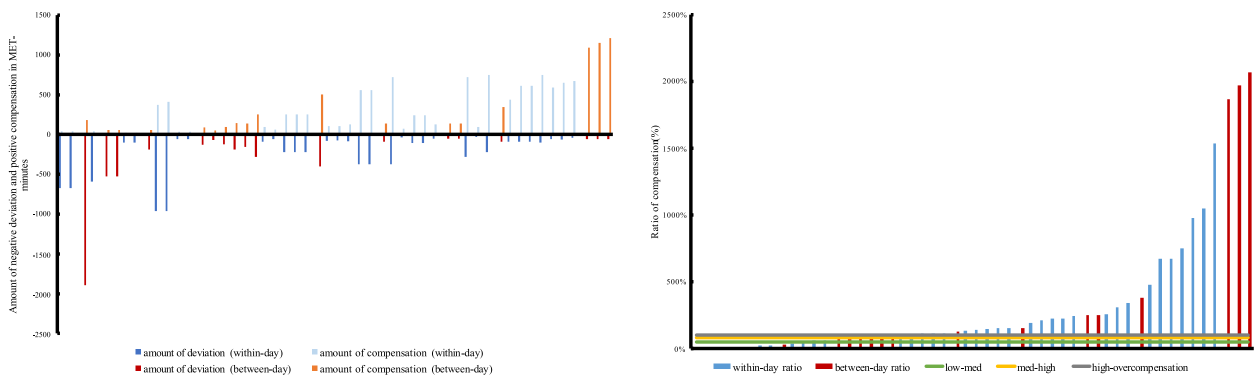

Fig. 2 Overall amount of negative deviation and subsequent positive compensation (left) as well as ratio of compensation (right) with the thresholds for low, medium and high partial compensation as well as overcompensation. Blue colors indicate the within-day compensation and red colors the between-day compensations. Each bar represents one compensatory behavior

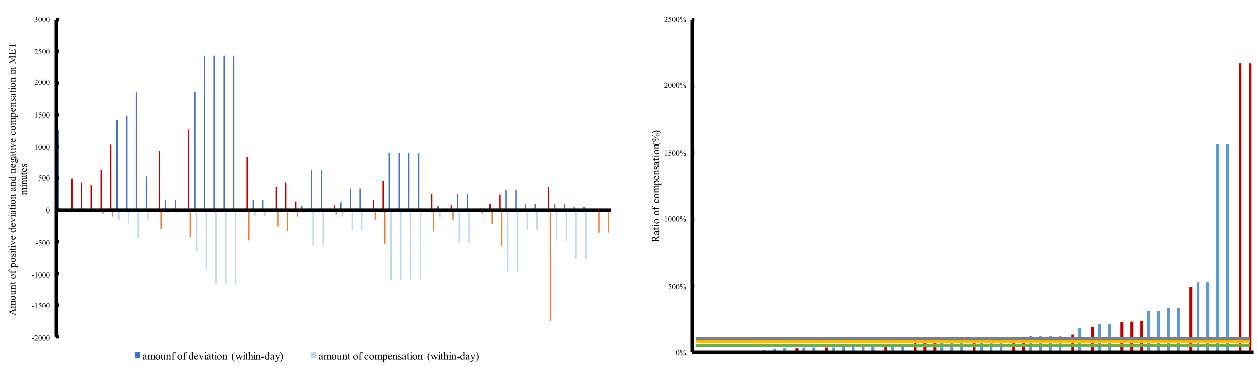

Fig. 3 Overall amount of positive deviation and subsequent negative compensation (left) as well as ratio of compensation (right) with the thresholds for low, medium and high partial compensation as well as overcompensation. Blue colors indicate the within day compensation and red colors the between-day compensations. Each bar represents one compensatory behavior

Fig. 3). In boys, the ratio of compensation ranged from 7 to 525%, and in girls the range was from 4 to 189%. Furthermore, the proportions of low, medium, high and overcompensation for negative compensation can be found in Additional file 7.

Lastly, regarding the timeframe, of all [$n=57$] negative compensatory behaviors, negative compensation occurred in 35 opportunities [61.4%] within-day, and in 38.6% between-day (see Additional file 6). Further, Fig. 3 shows the amounts of MET-minutes and Additional file 4 the amounts of MET-minutes for positive deviation and negative compensation within and between day. The ratio ranged in boys within-day from 14 to 525% and between-day the ratio of compensation was 7% to 490%. Ratio of compensation in girls ranged from 4 to 94% within-day and 8% to 189% between-day.

No Compensation

Deviations from the habitual PA level were not always compensated. Compensation [$n=198$] did not occur in 89 (44.9%) of 198 possible opportunities. Of these 89 possible compensation opportunities where no compensation occurred, 85 (95.5%) were negative deviations whereas just 4 opportunities with a positive deviation were not compensated. In boys there were 39 opportunities that were not compensated (36 negative deviation, $N=36$ [92.3%]; positive deviation, $N=3$ [7.7%]) and in girls there 50 opportunities that were not compensated (49 negative deviation, $N=49$ [98.0%]; 1 positive deviation, $N=1$ [2.0%]). Details about the amount of deviation in MET-minutes can be found in Additional file 8.

Qualitative Data

Interviews Topic 1: Awareness of compensation

The interviews were conducted on the comparison between habitual weekly schedule and activity diary. Regarding compensatory behavior, the participants were asked about the awareness of compensation. Amongst all compensatory behaviors, about half of the adolescents did not perceive that they had compensated ($N=8$) (*"I wouldn't call it a conscious decision to do sports, simply because I had time and she [her friend] also plays handball with me, she [her friend] also had nothing to do, so we just said, come on, let's go outside for a bit and the weather was nice anyway"*). Compensation occurs more often spontaneously in the situation than it is consciously perceived even if the compensatory analysis indicated a compensation. However, less adolescents ($N=5$) were aware of compensation in some opportunities, but not in all of their compensatory opportunities (example for awareness: Interviewer *"Okay so that was also a bit of a conscious decision that you said 'wow, the day before was very exhausting, very active, now I'm going to slow down a bit'"* and Adolescent: *"Yes, yes, yes"*; example for no awareness of the same adolescent:*"It was a spontaneous decision. My friend wrote me on Saturday and asked if I would like to play football with her [friend] spontaneously. And since it was just nice weather, I went of course with the bike, so that's how it came about from each other. And yes, but if she hadn't asked me, I wouldn't have gone anywhere either. I don't think so."*). Only one adolescent was aware of all the compensatory behavior he did (*"Yes, so it was quite consciously like 'okay, before I sit in the car for eight, nine hours now, I try to move more than usual in the morning"*).

Interviews Topic 2: Influences for compensation

As the perception of compensation indicated, there were often situational influences for compensation. Overall, in the present study we distinguished between internal and external influencing factors for compensation. Further, the influences for compensation differed between positive and negative compensation (see Table 3).

Positive Compensation—internal

Within the positive compensatory behavior, there were two internal and three external influencing factors identified each. As internal factors for positive compensatory behavior, the need of movement was one influencing factor mentioned by a few participants. This means that after a decrease of PA, participants felt a need for movement. This ended up in an extra activity or an increase of habitual PA (*"when I didn't have any training on Wednesdays, I had to do something for school that day, but I still went outside for a few minutes later, because I probably still had the urge to move, even though I already rode my bike today."*). Next, adolescents mentioned being physically active after decreasing because of the desire to move in a spontaneous way. Adolescents said *"I just feel it in this moment to be active"* or *"it has turned out this way"* without given any conscious influencing factor.

Positive Compensation—external

Regarding external factors for a positive compensatory behavior, the most frequently mentioned influence was social support. Having a friend to be active with supported a positive compensation after a decrease in PA (*"My friend comes over to my house and asked me if I want to play football with her."*). Good weather conditions were also cited as an influencing factor for compensation (*"in the evening I played outside because the weather was good"*). Adolescents perceived the weather as an incentive to be more active/do extra activity at another time after inactivity/less PA. The last external factor mentioned by the participants was the encouragement/enforcement of activity from the parents. One female

Table 3 Influencing factors for compensation

Positive compensation

Internal		**External**	
Spontaneity and Desire	*So it was just ...it turned out that way.* *I just felt like it and had the desire.*	Weather	*[...] actually, because the weather was good.*
Need of Movement	*[...] to be a bit more active and active and somehow compensate the whole thing with something else because training is cancelled.*	Friends	*So if the friends writes that he [the friend] has no time, then I would do something with him, but otherwise not.*
		Coercion	*Our mothers have agreed that we will go and collect leaves in the forest. The decision for an activity was from our parents.*

Negative compensation

Internal		**External**	
No desire	*Sometimes you don't feel like it at all.*	Major event	*[...] also because on Sunday I clearly felt the sore muscles from this tournament and I also just took a day as a break.*
Relaxing	*I wouldn't go because I've already moved.*		
Resting	*[...] because I just had so much other strenuous activity.*		

Note: Red color = greatest importance, orange = medium importance and green = low importance participant mentioned that her mother/parents told her to go out because training was cancelled and thus organized a meeting with her friends and their parents to go in the forest and collect leaves (*"Our mothers actually made it out that we would then go and collect leaves. That was a decision made by the parents, that we should move around, go out, play and collect leaves.").*

Negative Compensation – internal

Overall, three internal influences were identified for a negative compensation. First, participants mentioned that they were exhausted because of an increase of PA and thus, needed a rest (*"So I was very exhausted, especially in the legs, because I had been jogging two days before, then soccer tournament and then it was a bit exhausting, so I did less afterwards"*). Further, adolescents wanted to relax after additional PA because they felt like they had already done enough (*"I didn't go [to training], because I've already moved"*) even if they didn't feel really exhausted. In this context, a few adolescents also said that they didn't have a desire to continue with the habitual activities after they had more or an extra activity and thus, they compensated negatively.

Negative Compensation – external

In addition, an external influencing factor for a negative compensation has also been identified. Participants took a rest from their habitual behavior and were more inactive after a big event like a tournament (*"So as far as a workout is concerned, also because on Sunday I clearly felt the sore muscles from this tournament and I also just took a day as a break, so to speak, after this day full of activities on Saturday"*).

Interviews Theme 3: Influences for not compensating

Besides influencing factors for compensating, our interviews identified a wide range of internal and external influences for not compensating, positive and negative. An overview can be seen in Table 4 and in the following paragraphs a more detailed explanation.

Positive possible – internal

Besides the influences for compensation, the study also focused on influencing factors why adolescents did not compensate. The majority of adolescents didn't see the need for more PA after they had less PA than usual (*"I don't feel the need"*). In some cases, they were happy about the spontaneous/unplanned reduction in habitual PA (*"it was not bad that training was cancelled"; "I was happy that physical education was cancelled and I then also no longer really had the need not to move"*) or were not aware of the lack of PA (*"then I don't even realise that half an hour of exercise is now missing."*).

Negative possible – internal

Opportunities with more PA than usual could have been compensated negatively, but there were also opportunities that were not compensated by less PA. Some adolescents mentioned that their lack of negative compensation was prompted by the fun/joy of movement related to the additional activity. In other words, they didn't compensate for the activity because it was something they enjoy (*"I do it [jogging—even if there was more activity than usual in the morning] because I enjoy it."*). Additionally, in some instances more PA than usual was perceived as profitable and good for health (*"I do more, because it's good for my health").*

Positive possible – external

One external influence why adolescents did not compensate the decreased activity is that they perceived a lack of social support. Thus, they decided to be rather inactive than being active alone (*"I always have to make appointments with friends earlier [...] I don't like being active alone (so I did no activity)"; "So if they don't have time [...] then I don't try to get the (decreased) activity somehow"*). Further, sickness could be a barrier to be active and thus, a loss of activity wasn't compensated.

Negative possible – external

Some adolescents reported that they did not compensate negatively between-days because they thought of each day as a reset from the previous day (*"that is then simply so that I do it again the next day as normal."; "No (I did not do less after an increase of PA), that's just the way it is then, that I just made more".*) and thus complied with the typical structure of the following day (*"I always try to have a structure routine"*). Lastly, some reported that they did not compensate when activities were obligatory, such as taking part in physical education lesson (*""After all, it's obligatory, I can't avoid it."*).

Discussion

The aim of the present study was to analyze and identify compensatory behavior in the context of German adolescents aged 11–15 years. Overall, in our study 55.5% of all opportunities were compensated (57 negatively and 52 positively). Of all compensatory behavior, negative compensatory behavior was observed slightly more often than positive compensatory behavior. Compensatory behavior in either direction (i.e., positive or negative) seemed to occur equally within-day and between-day, with no clear patterns emerging. The main enablers for compensating positively were friends/social support and influences for not compensating negatively were maintenance of the habitual schedule as well as hedonism/enjoyment of activities.

Table 4 Influencing factors for no compensation

No positive compensation

Internal		External	
Joy about less activity	*I was rather pleased that we didn't have physical education lesson.*	Friends	*So if they don't have time […] then I don't try to get the activity somehow.* *I always have to make appointments with friends earlier […]; I don't like being active alone.*
No awareness of less activity	*[…] then I don't even realize that half an hour of training was missing.*	Sickness	*[…] because my cardiovascular system was not yet ready for physical activity.*
No need for movement	*I don't feel the need.*		

No negative compensation

Internal		External	
Health and training effect	*If I do more, it's good for me and my health status.*	Obligation	*After all, it's obligatory, I can't avoid it.*
Fun during movement	*I do it [more physical activity] because I like it.*	New day/routines	*[…] that is simply so that I behave the next day as normal.* *I always try to have a structured daily routine.*

Note: Red color = greatest importance, orange = medium importance and green = low importance

Occurrence of compensation

Compensation occurred in just over half of possible compensation opportunities, with just over half of these occurrences being negative compensatory behavior. Whilst the occurrence of negative compensation was slightly more dominant than positive compensation in the present study, this trend was also observed in another study focusing on pre-adolescent girls [43]. In this study, all possible negative compensation opportunities were compensated negatively, whereas just 14.2% of possible positive compensation opportunities were positively compensated [43].

Compensation timeframe and ratio

Overall, compensatory response can occur within-days, between-days as well as over (several) weeks [21–23], nevertheless, within our study we could only focus on compensation on a within-/between-day basis for one week. Regarding the timeframe of compensation in our study, data indicated that of all compensatory opportunities, 63.3% of all compensatory opportunities took place within-day. This was also stated in the study of Swelam et al. [31], who postulated that compensation scarcely occurred between-days because there is more like a reset each day. Nevertheless, this study did not include "real" data and instead participants were just asked in the interview about potential compensatory behavior. In general, this trend is in contrast with other findings [21, 22] stating that compensation mainly occurs between-days. However, Gomersall et al. [21] summarized more studies assessing between-day activity behavior compared to the review of Beck et al. [22], which could be a possible explanation for the discrepancy in the findings.

Regarding the ratio of compensation, the results across subjects were largely heterogenous, with high proportion of overcompensation (e.g., > 100% compensation), especially for positive compensation. One influencing factor for the heterogenous results could be enjoyment of PA as this seems to influence the degree of compensation [31]. For example, children positively compensate an increase of PA levels by 80% when they enjoyed the additional PA versus only a small partial compensation of < 50% when they did not enjoy the additional PA [35].

Influencing factors for compensatory behavior

Overall, from the qualitative interviews we identified various factors from the qualitative interviews trying to explain activity compensation in adolescents. The most frequently mentioned influencing factor for negative compensation was related to relaxing after prolonged PA, either with or without being exhausted. In the first case, adolescents believed they could relax because they did more PA than usual before, even if they were not exhausted or tired. This could be explained by the missing awareness of their overall PA [44] in combination with the unawareness of health benefits of sufficient activity levels [18, 45]. In our study, health and training effects of the additional activity were also mentioned as one influence for not compensating the additional PA. Nevertheless, only few adolescents did not compensate additional PA by less PA at another time point. Thus, improving awareness of activity and health benefits may therefore be a crucial initial component of promotion campaigns, even if there are a few interventions that already consider this point [18, 46–48]. In the second case, there were also situations in which adolescents reported tiredness, sore muscle, or overexertion. These symptoms occurred mostly after bigger events like one-day tournaments in a specific sport (external influence). This influencing factor was also identified in the Australian study with elementary school children [31] and is also in line with the underlying mechanism of the ActivityStat hypothesis that each individual has a level of PA that is tolerable and PA above that tolerance threshold would be compensated [21]. In this respect, there may be instances where, what we've considered as 'negative compensation', serves as an important and biologically necessary mechanism to manage fatigue. The consideration of such nuances may be warranted in future intervention design and compensation research.

Regarding negative compensation, an interesting point was that negative compensation did not occur when the following activities were obligatory (e.g., physical education, training) or as a result of parental coercion. In this context of compensatory responses due to obligation or force, we would like to mention that the ActivityStat hypothesis does not totally fit in. The hypothesis is not suitable to explain thise cases in which compensation does not occur due to a biological mechanism. Here, compensation rather occurs due to external force. However, compensation due to self-obligating activities which are accompanied by enjoyment of the activity, is in line with Rowlands et al. [49] who argued that "hedonistic activities" (e.g. such as playing in a sports team) may override the biological control. Further, adolescents also mention that they want to stick to their routines and thus, did not cancel any of their activities to compensate the past additional activities. This finding is consistent with a previous study that reported that routines (i.e., overall and organized activities) helped children maintain a level of after school activity, regardless of whether they had been more active than usual at school [31]. Lastly, the results suggested that adolescents see each day as a new day, and thus, they do not adjust their PA the next day. Similar findings were reported by Swelam et al. [31], which explained this phenomenon as a 'reset' at the end of the day. In summary, it seems that routines as well as (self-)obligatory activities may be important indicators in avoiding negative compensation.

Besides the negative compensation, compensation occurred also in a positive direction. In this context, external influences were mentioned more often than internal influences. As external factors, social support was the most mentioned influence for positive compensation. In contrast, in cases where friends didn't have time for co-participation, positive compensation was less likely. This is in line with existing literature stating that social support of peers is an important determinant and facilitator of PA [50–53]. Similar, Swelam et al. [31]

indicated the relevance of family and friends also as influences for compensating positively. Thus, it seems that social support is also a facilitator of positive compensation. Lastly, good weather was also a factor that fostered positive compensation. Good weather is one of the strongest predictors of PA in children and adolescents [54–56]. Bad weather was identified to have the opposite effect [31], and may hinder children and adolescents being physically active and thus, compensating positively.

In the context of internal influences for positive compensations few adolescents mentioned a need for activity after a decrease of PA levels. However, these adolescents could not trace back where it was stemming from. Similar mechanisms were found in Australian elementary school children whose parents reported that their children had a 'need' to do more PA in response of low PA levels [31]. In that study, this was expressed by the parents as "just how [their child] was feeling". In the current study, adolescents mentioned a kind of feeling and desire for doing activities which was supported the findings of the previous study. Overall, this behavior typically occurred spontaneously and may also be related to the (lack of) perception of compensation. This finding would also be supportive and indicative of the hypothesized biological control of PA, as it was hypothesized that, "A biologic regulator of physical activity in humans could operate by controlling the level of spontaneous, mainly involuntary PA (NEAT) or by increasing motivation to participate in planned voluntary activities." [57] (p.122).

In summary, the findings of this investigation assume kind of a malleability of the ActivityStat hypothesis with the ActivityStat hypothesis postulating not a rigid mechanism that is amenable to external influencing factors, such as environmental or social influences. We can consider this as a complex interaction of needs or desires for movement or rest with one's (social and physical) environment (e.g., social support, weather, routines). For further exploration of compensation thresholds and timeframes a combination of objective and subjective measurement methods is needed to get deeper insights on these mechanisms.

Awareness of compensation

In the present study, only few adolescents were aware that they compensated their increased/decreased behavior. It seems that it is more a situational behavior which is not consciously performed because of the awareness of less/more activity than usual before. This is in contrast with a qualitative study from Australia [31]. In this study, most elementary school children perceived their compensatory behavior while only some participants lacked awareness of any compensatory response or thought that compensatory behavior did not take place. The differences between these two studies could be due to differences in the study design. In the present study, data was driven from weekly schedules as well as diaries whereas in the study of Swelam et al. [31] the participants were asked to think about a hypothetical day they would have had lots of activity at school and how this would influence their activity behavior after school (same for between-day). As this is not based on "real" data, this is limited to the potential difference between claim and reality.

Practical implications

The findings of the present study may also have some important practical implications. Firstly, social support seems to be helpful in avoiding negative compensation following an increase of PA, as well as supportive of positive compensation following less PA than usual. Further, it is important that adolescents find activities they like to do as such "hedonistic activities" seem to override the biological control. Thus, these activities may subsequently result in less negative compensatory behavior, especially in the instance of habitual hedonistic activities. In this context, routines may also be important in avoiding negative compensation as adolescents want to stick to their routines. As such, further support for adolescents in finding active routines may be warranted.

Strengths & Limitations

The study's novelty is grounded in examining actual compensatory behavior and subsequent influencing factors of compensatory behavior in adolescents. Despite the small sample size ($N=15$), a high volume of activity data was yielded (382 activities overall). That makes it possible to differentiate between positive, negative and no compensation within the sample and within subjects. In addition, the used diary was programmed exactly for our research question and enables us to achieve the aim. This is also the first study, assessing the amount of deviation as well as the amount of the compensatory behavior.

However, there are several limitations that should be stated. Overall, the sample size ($N=15$) is quite small. Given the data collection methodology (i.e., smartphone-based app), adolescents without a smartphone could not participate in the study. Further, the habitual weekly schedule was self-reported and occurred as a once-off assessment (i.e., in one week rather than across several weeks). As such, this could be associated with social desirability by indicating more PA behaviors than usual. Furthermore, this method did not allow for checking the validity of the habitual behavior. In this context, the subjective and retrospective assessment of activities within the weekly schedule and the diary carries the risk for recall bias. Compensatory analysis in our study could only be conducted on a within-/between-day basis for one week, and not on timeframes greater than one week, even if this is also a potential timeframe for compensation [21]. Additionally, we did not consider sedentary behaviors, even if this is important as compensation could also occur with regards to sedentary behaviors. Lastly, the Youth Compendium of PA [34] was utilized to calculate the MET cost for each activity. Nevertheless, if an activity wasn't listed in the Youth Compendium, the MET cost was estimated based on similar activities, that could have limited the accuracy of the data analysis,

Conclusion

This study provided new insights into occurrence and influencing factors for compensatory behavior in adolescents. Overall, 55.1% of deviations were compensated. The occurrence of positive and negative compensatory behavior were similar, with no obvious patterns emerging. Compensation occurred within-day slightly more often than between-day, which may be related to the mental presence of the activity as well as the reset at the end of the day. Overall, it seems that compensation is a complex interaction between biological control and influencing factors. For instance, social support seems to facilitate positive compensation, whilst routines and hedonistic activities may assist in avoiding negative compensatory behavior. Thus, it seems to be helpful to support individuals in their search for hedonistic activities as well as in the establishment of routines.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-023-17519-1.

Additional file 1. Weekly Schedule.

Additional file 2. Interview Guide – Compensation Qualitative Study.

Additional file 3. Calculation of Compensation.

Additional file 4. Amount (range) of deviation and compensation for positive and negative compensation for overall, boys and girls as well as within- and between-day.

Additional file 5. Prevalence (%) of low, medium and high partial positive compensation as well as positive overcompensation.

Additional file 6. Prevalence (N) of positive and negative compensation within- and between-day.

Additional file 7. Prevalence (%) of low, medium and high partial negative compensation as well as negative overcompensation.

Additional file 8. Amount (range) of deviation that was not compensated.

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Authors' contributions

Conceptualization: F.B., A.K.R.; Methodology: F.B., B.A.S., U.D., C.K., A.K.R.; Formal analysis and investigation: F.B.; Writing—original draft preparation: F.B.; Writing—review and editing: F.B., B.A.S., U.D., C.K., A.K.R.; Supervision: A.K.R.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The study was approved by the local Ethics Committee of the Friedrich-Alexander-Universität Erlangen-Nürnberg (Ref. No. 23–31-S) and was in accordance with the 1964 Declaration of Helsinki. All participants and their legal guardians provided written informed consent for study participation. Participation in the study was voluntary and every participant received a gift worth 10 €.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Publisher's Note

Summary

This study provides new insights into prevalence and reasons of compensatory behavior in adolescents. Overall, 198 situations with deviations >20% were identified. Of these, 109 situations were compensated (69 within-day, 40 between-day). Negative compensation took place in 57 opportunities, whereas 52 opportunities were compensated positively. The most mentioned reasons for positive compensation were social support by friends and good weather, as this motivates adolescents for being physically active. Tiredness and a lack of "need for movement" were mentioned predominantly as reasoning for negative compensation. No negative compensation occurred because adolescents wanted to stick to their routines or participated in hedonistic activities which kept them active. With the present findings, it seems that compensatory behavior is a complex interaction between biological control and influencing factors. Especially social support appears to play an important role to compensate positively or to avoid negative compensatory behavior. Further, it seems to be helpful to support individuals in their search for hedonistic activities as well as in the establishment of routines. To illustrate the importance of social support and the family environment, we complete the thesis by Manuscript F, which focuses on family predictors and the influence on changes in PA levels.

4.2.2 Manuscript F: Family Predictors of Physical Activity Change during the Covid-19 Lockdown in Preschool Children in Germany

Beck, F., Schmidt, S. C. E., Woll, A., & Reimers, A. K. (2022). Family predictors of physical activity change during the Covid-19 lockdown in preschool children in Germany. *Journal of Behavioral Medicine*. https://doi.org/10.1007/s10865-022-00382-7

Introduction

The previous findings demonstrated the existence of an activity compensation in children and adolescents. Further, various factors were identified that could explain compensatory behavior. Especially social support was associated as one important variable explaining positive compensation (increasing the PA after a decrease of PA) or helping to avoid negative compensation (decreasing the PA after an increase of PA before). In chapter 3.1.2 we illustrated the Covid-19 pandemic as one perturbation that led to changes in the habitual PA behavior in children and adolescents. With the following article, we investigated the influence of the family environment, specifically SES, parental support, and having siblings on Covid-19-related changes of PA and screen time behavior in 317 (170 boys, 147 girls) German preschool children using longitudinal data of the MoMo-Study.

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Family predictors of physical activity change during the COVID-19 lockdown in preschool children in Germany

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Abstract
The COVID-19 pandemic is associated with crucial changes in children's daily life including their physical activity (PA) and screen time (ST). Among preschool children, the family represents an important factor for sufficient PA levels by being the gatekeeper for PA. Thus, the aim of this study was to investigate the influence of the family environment, specifically SES, parental support, and having siblings on COVID-19-related changes of PA and ST behavior in 317 (170 boys, 147 girls) German preschool children using longitudinal data. Our results indicate a decline in total amount of sports-related PA, an increase in outdoor play, as well as an increase in leisure ST in preschool children. The changes in total amount of PA differed between children with different levels of parental support as well as in dependence on having siblings. Furthermore, levels of outdoor play and ST in preschool children were influenced by environmental factors like having access to their own garden. We conclude that the family environment (parental support as well as physical environment) is highly relevant for PA and ST levels in preschool children. To provide every child with PA opportunities during potential future lockdowns, restriction policies should be adapted and parents need sophisticated information about the importance of their support and thus the PA levels of their children.

Keywords Preschool · COVID-19 · Physical activity · Family

Introduction

In mid-December 2019, the first cases of the new Coronavirus (SARS-CoV-2) causing respiratory disease (COVID-19) in humans were reported from hospitals in Wuhan, China (Wu et al., 2020; Zhou et al., 2020). Due to the global spread of the virus in the subsequent weeks and months, the rising number of cases, and the high mortality, particularly among the elderly, the WHO declared COVID-19 as a global pandemic on March 11th, 2020 (World Health Organization, 2020) and measures to slow down the spread of the virus were implemented. The federal states of Germany closed preschools for children aged 3–5 years, schools, sports clubs, gyms, and other leisure institutions relevant to children's and adolescents' organized physical activity (PA) in March 2020. Furthermore, the government enforced physical distance measures and contact restrictions, allowing no more than two people from different households to meet in public space (Press and Information Office of the Federal Government, 2020a). Practicing organized sports was impeded due to the closing of public sports facilities and sports clubs. However, non-organized sports like going for a walk or playing outside remained allowed if done alone or with people from the same household (Press and Information Office of the Federal Government, 2020b). The lockdown was imposed until 3rd May 2020 (Press and Information Office of the Federal Government, 2020c).

The COVID-19 outbreak and the following mitigation policies, especially the closure of preschools and home office for parents, resulted in crucial changes in children's daily life and their movement behaviors (PA, sedentary behavior including screen time (ST)) (Bates et al., 2020; Chen et al., 2020; Guan et al., 2020; Hall et al., 2020). These policies foresee a revolution of one's habits and lifestyle including the possibility to remain physically active during a forced

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isolation by adapting the movement and PA behavior (e.g., unstructured PA instead of organized sports opportunities, online PA offers for children) (Chirico et al., 2020). This is important as regular PA and low sedentary time are associated with numerous health benefits in childhood and adolescence (Poitras et al., 2016). In this context, we would like to differentiate PA and sedentary behavior as this explains why we assessed PA as well as ST. PA is defined as any bodily movement produced by skeletal muscles that requires energy expenditure. Thus, PA refers to all movement including during leisure time, for transport to get to and from places, or as part of a person's work (Caspersen et al., 1985). On the other hand, sedentary behavior is different from being physically inactive, as it is possible to meet PA guidelines and still spend a large amount of time sitting. Thus, these two behaviors do not directly displace each other (Pearson et al., 2014) and are both included in the present study. In particular, as a result of regular PA as well as of reduced sedentary time, children improve their cardiovascular (Ekelund et al., 2012) and cardiometabolic (Ekelund et al., 2012; Poitras et al., 2016) health and reduce their risk of obesity (Committee, 2008; Hong et al., 2016; World Health Organization, 2009). Additionally, PA is associated with better mental health in children (Biddle et al., 2011) and adolescents (Rodriguez-Ayllon et al., 2019). Especially for preschoolers, commonly including children aged 2–5 years who are not old enough to go to a formal school, PA and bodily movement are also needed for healthy growth and cognitive, social, and emotional development of the child (Berk, 2013; Poitras et al., 2016). Furthermore, PA in early childhood PA is tracking through youth into adulthood and therefore contributes to an active lifestyle throughout one's lifespan (Telama et al., 2014).

Even if there is a lot of knowledge about the benefits of PA, research on PA and sedentary behavior during the COVID-19 pandemic indicated predominantly PA decreases (Aguilar-Farias et al., 2020; Carroll et al., 2020; Clarke et al., 2021; Guan et al., 2020; Jauregui et al., 2021; Kracht et al., 2021; Lopez-Bueno et al., 2020) whereas sedentary time including ST increases (Aguilar-Farias et al., 2020; Jauregui et al., 2021; Kracht et al., 2021; Lopez-Bueno et al., 2020) in preschool children compared to pre lockdown levels. Existing COVID-19 studies were cross-sectional studies using retrospective pre-COVID-19 data and considered only slightly differences in PA changes related to the social environment, even if PA levels differ between social variables as can be seen in pre-lockdown data among preschool children (Reimers et al., 2019). Data gathered before the pandemic showed that preschool children in Germany reduced their PA in unorganized activities from about 49 min per week (2003–2006) to 36 min per week (2009–2012) and 24 min per week (2014–2017) (Schmidt et al., 2020b; Schmidt et al. 2017) but slightly increased their organized sports activities. Thus, it would be quite interesting to see the changes of unorganized and organized PA as organized sports opportunities could not take place during the lockdown. Studies before the pandemic also indicated that the support of their family members seem to play an important role in promoting opportunities for PA among preschool children by being the gatekeeper for PA (Bingham et al., 2016; Gariguett et al., 2017; Hinkley et al., 2008; Loprinzi et al., 2010; Mitchell et al., 2012; Schmutz et al., 2017). Parental support contains different types, but there is no completely agreed-upon structure of the components in the literature (Rhodes et al., 2019). However, typically it includes instrumental or logistic support (e.g. transportation to activities), informational support (e.g. importance of PA within the family), emotional support (e.g. parental interest in child's PA), and companionship (e.g. parent and child doing PA together) (Pyper et al., 2016; Uchino, 2009). Due to the closure of preschools during the pandemic, preschool children require greater parental support which may mean managing and supervising children's activities and behaviors was more challenging for these families, particularly if parents were working (Prime et al., 2020). These circumstances are also reflected in PA levels in preschool children measured within a qualitative study: it was concluded that parental support for children's PA during the pandemic was easier when one parent was not working and therefore, the children of non-working parents accumulated higher PA levels than children whose parents both were working (Clarke et al., 2021). Furthermore pre-pandemic research suggested differences in children's PA and ST levels related to their parents' educational level and socioeconomic status (SES) with higher PA and lower ST in children from families with higher SES (Aguilar-Farias et al., 2020; Schmidt et al., 2021; Tandon, Zhou, Sallis, et al., 2012). Interestingly, during the pandemic, children whose parents are working from home and have a higher income or SES, tend to restrict their children's PA more, while at the same time may provide more opportunities to engage in ST (Aguilar-Farias et al., 2020; Clarke et al., 2021; Jauregui et al., 2021). A further social variable that was associated with higher PA levels before the pandemic is having someone to play with (Sigmund et al., 2021). In times of restrictions, siblings seem to increase the likelihood to be physically active. Thus, children having siblings were significantly more active during the lockdown than children without siblings (Aguilar-Farias et al., 2020; Clarke et al., 2021; Jauregui et al., 2021; Pombo et al., 2020). Lastly, outdoor opportunities and access to green spaces are associated with preschool children's PA levels (Benjamin-Neelon et al., 2019; Gray et al., 2015). However, with the closure of public green spaces, it was difficult for children to be physically active outdoors, especially if families haven't their own garden. Data confirmed this relationship by indicating that children living in apartments without access to outdoor space revealed lower PA levels compared with children in houses or greater living areas (Aguilar-Farias et al., 2020; Clarke et al., 2021; Jauregui et al., 2021; Okely et al., 2021).

However, while research regarding changes in PA and ST levels in children and adolescents exists, only few studies investigated the influence of COVID-19 lockdown on preschool children. In particular, there is, until now, no study for Germany focusing exclusively on preschool children. Furthermore, only a few of the existing studies investigated changes from pre to during pandemic PA and ST levels by taking social variables like the family environment into account (Aguilar-Farias et al., 2020; Clarke et al., 2021; Jauregui et al., 2021). In addition, most of the previous COVID-19 studies are cross-sectional and used retrospective data for analysis of the changes.

Therefore, the aim of the present study is to investigate the influence of the family environment, specifically SES, parental support, garden ownership, and having siblings on COVID-19-related changes in PA and ST behavior in German preschool children aged 4–5 years using longitudinal data.

Material and methods

The STROBE guidelines (Vandenbroucke et al., 2007) guided the writing of the current manuscript.

Study design

The Motorik-Modul (MoMo) Study is a nationwide longitudinal study on PA, motor performance, and health in children and adolescents from Germany and has been started in 2003 (Wagner et al., 2014; Woll et al., 2021). Until now, besides the MoMo baseline study (2003–2006), three further measurement time points (waves) have been taken with Wave 3 starting in August 2018. This wave was planned to be finished in June 2020. Due to the COVID-19 situation and the related lockdown in Germany, the study had to be interrupted in March 2020. Alternatively, a MoMo COVID-19 lockdown study was conducted from 04/20/2020–04/30/2020. All participants of the regular MoMo wave 3 were asked to take part in this COVID-19 lockdown study and to answer an online questionnaire about their PA behavior during the lockdown. The individual time span between the two measurements of MoMo wave 3 and the MoMo COVID-19 lockdown study ranged from 1 to 27 months.

The study was conducted according to the Declaration of Helsinki. Ethics approval was obtained by Charité Universitätsmedizin Berlin ethics committee, by the University of Konstanz, and the ethics committee of the Karlsruhe Institute of Technology (KIT) (Wave 2 and 3, a positive ethics vote was given on 23 September 2014 by the ethics committee of the KIT). The Federal Commissioner for “data protection” and “freedom of information” and the Federal Office for the Protection of Data were informed about the study and approved it. Children and adolescents participated voluntarily and every participant received a gift worth 20€. They provided written informed assent and (parental) consent. This paper reports pre-COVID-19 data that was derived from the third follow-up of the MoMo Study (the interrupted wave 3) and data from the COVID-19 lockdown study (during-COVID).

Participants

MoMo Wave 3 participants (pre-COVID-19) were selected based on a nationwide multistage sampling approach with two evaluation levels to ensure the best representativeness possible (Schmidt et al., 2020a). First, 167 sampling units were systematically selected from an inventory of German communities which assesses the level of urbanization and geographical distribution (Lampert et al., 2014). Second, an age-stratified sample based on the official population registers was drawn and invited to the study.

Overall, 2843 participants of MoMo Wave 3 (preliminary response 25.2%) were contacted for the within-COVID-19 assessment, and data from 1711 participants (4–17 years old) were gathered. A total longitudinal response of 63.6% was achieved. The reasons for non-participation are unknown due to data protection regulations. In this paper, we analyzed the data of 317 preschool children (mean age: 5.04 ± 0.55) (see Table 1).

Data collection

Within the MoMo wave 3 data collection participants were invited to examination rooms within a distance of 15 km from their homes and answered the MoMo PA questionnaire (MoMo-PAQ) (Schmidt et al., 2016) on laptops. For preschool children, parents filled in the questionnaire (proxy-report). For the Follow-up survey during the lockdown (during COVID) parents answered the questionnaire through a link sent to them via e-mail. Further information about data collection has been published elsewhere (Schmidt et al., 2020b).

Measures

Demographics

Demographic data were based on information from MoMo Wave 3 data including age, sex, and a multitude of socioenvironmental and socioeconomic variables. For the present study, we included the SES (Lampert et al., 2014), as well

Table 1 Sample characteristics

		4-year-olds	5-year-olds	Total
Total [n]		150	167	317
Boys [n (%)]		79 (52.7%)	91 (54.5%)	170 (53.6%)
Girls [n (%)]		71 (47.3%)	76 (45.5%)	147 (46.4%)
Age pre COVID (years; M ± SD)		4.54 ± 0.28	5.50 ± 0.28	5.05 ± 0.55
SES [n (%)]	Low	16 (11.0%)	20 (12.3%)	36 (11.7%)
	Mid	108 (74.0%)	118 (72.8%)	226 (73.4%)
	High	22 (15.1%)	24 (14.8%)	46 (14.9%)
Garden ownership (yes) [n (%)]		121 (80.7%)	149 (89.2%)	270 (85.2%)
Siblings (yes) [n (%)]	Active	81 (55.1%)	91 (54.5%)	172 (54.8%)
	In active	43 (29.3%)	43 (25.7%)	86 (27.4%)
	No siblings	23 (15.6%)	33 (19.8%)	56 (17.8%)

M mean; *SD* standard deviation

as garden ownership. Individual SES was defined by the total household income per household member as well as the educational and professional status of the parents. Both parents were separately asked about their educational and professional status (Lampert et al., 2014). Preschool children with separated parents were assigned to the SES of the parent they lived with. The sum score was then categorized by quintiles of the whole MoMo Wave 3 sample into low (first quintile: < 9), medium (9–17), and high (fifth quintile: > 17) SES. Detailed information about this approach can be found elsewhere (Lampert et al., 2014).

Physical activity

To assess PA we used the MoMo-PAQ with sufficient reliability and validity (test–retest reliability: ICC ≤ 0.68) (Jekauc et al., 2013). Participants were asked about their sports activity in organized (sports club, school) and nonorganized leisure sports activities. Parents could then answer questions about frequency, duration, type, and intensity of their children engaging in each setting by proxy-report. Items were then combined in one index (= total amount of sports-related PA) that reflects the daily minutes with organized (school and sports clubs) and non-organized PA. Detailed information about the PA measure has been published elsewhere (Schmidt et al., 2020b).

Furthermore, participants were separately asked about minutes per day of non-organized playing outside (Schmidt et al., 2016).

Recreational screen time

ST of the preschool children was measured via proxy-reported ST behaviors by the parents. Parents were asked to report their preschoolers' time spent watching TV, playing games on any device, and using the internet for recreational use separately on weekdays and weekends using a 7-point scale including (almost) never, 15 min per day, 30 min per day, 1 h per day, 2 h per day, 3 h per day, and 4 h per day (Mathers et al., 2009). ST was summed up to gain a total amount of recreational ST in minutes per day.

Social support

Social support was assessed by parental support as well as having an (active) sibling. The parental support scale includes eight items and could be answered on a four-point rating scale (1—"not at all" to 4—"very important") (Jekauc et al., 2013). Higher scores indicated higher perceptions of social support. The scale was divided into four subscales with two items each. Parents then reported (proxy) following questions for their preschool child: emotional support ('How important is sport in your family?' and 'How important is it to your parents that you do sports?'), instrumental support ('How often are you driven to sports venues by your parents?' and 'Do your parents support you in your sports activity?'), informational support ('How interested are your parents in your sport?' and 'How often is your sport a topic of conversation in your family?'), and parental companionship ('Do your parents engage in sports with you?' and 'How often do your parents watch you doing sports?') (Reimers et al., 2012). Furthermore, participants were asked "Is at least one of your siblings physically active on a regular basis?" and this could be answered by "yes", "no" or "I don't have siblings".

Data analysis

All statistical tests were conducted using IBM SPSS 27 (IBM Corporation, Armonk, NY). Descriptive statistics for age, gender, SES, as well as garden ownership, and sibling were calculated and separated for 4- and 5-year-olds.

Separate single factor repeated measurement ANOVAs were used to analyze the influence of gender, social support through the family, SES, and the fact whether the child has access to an own garden on the change in PA and ST to prevent overparameterization. Statistical significance was set to $p<0.05$.

Results

Overall, 170 boys (53.6%) and 147 girls (46.4%) were included in the present study (Table 1). Overall, the mean age pre COVID-19 was 5.05 ± 0.55 years. Most of the preschool children had a mid SES (73.4%) and access to their own garden (85.2%). Regarding siblings, only 17.8% had no siblings whereas 54.8% had an active sibling.

Table 2 shows influencing factors on the change in the total amount of sports-related PA from before to during the COVID-19 lockdown. First of all, the total amount of sports-related PA did not significantly decrease from pre to peri lockdown in boys and girls ($F_{1,305}=1.59$; $p=0.21$; $p.Eta^2=0.005$) with no significant differences between boys and girls. Parental support (emotional, informational instrumental, and companion), as well as siblings, influenced the total amount of sports-related PA in preschool children. These main effects revealed significance with medium effect sizes. Related to an interaction, descriptive data indicated a greater reduction of sports in preschool children with lower parental support and having an inactive sibling. However, rmANOVAs did not reveal significance for the time*factor interaction. SES as well as having an own garden did not influence the total amount of sports-related PA in preschool children.

Table 2 Factors influencing the total amount of sports-related PA in 4–5 old children before and during the COVID-19 lockdown in Germany (MoMo Study)

Total amount of sports-related PA [minutes per week]							
Age 4–5 years	Descriptives				rmANOVA		
Factor	Value	n	Pre (M ± SD)	Peri (M ± SD)	Time	Factor	Time*factor
Gender	Boys	170	117.4 ± 79.4	98.8 ± 204.4	$F_{1,305}=1.59$ $p=0.21$ $p.Eta^2=0.005$	$F_{1,305}=0.40$ $p=0.53$ $p.Eta^2=0.001$	$F_{1,305}=0.06$ $p=0.80$ $p.Eta^2<0.001$
	Girls	147	122.6 ± 98.0	110.1 ± 201.3			
Parental support: emotional	Low (< 2.5)	35	93.8 ± 91.1	26.7 ± 91.6	$F_{1,302}=3.46$ $p=0.06$ $p.Eta^2=0.011$	$F_{2,302}=7.69$ $p<0.01$ $p.Eta^2=0.048$	$F_{2,302}=1.28$ $p=0.28$ $p.Eta^2=0.008$
	Med (2.5–3)	157	111.8 ± 80.8	95.9 ± 183.6			
	High (> 3)	113	140.2 ± 93.8	139.5 ± 243.8			
Parental support: informational	Low (< 2.5)	34	81.1 ± 77.8	30.9 ± 77.3	$F_{1,300}=2.73$ $p=.10$ $p.Eta^2=.009$	$F_{2,300}=9.14$ $p<0.01$ $p.Eta^2=0.057$	$F_{2,300}=0.48$ $p=0.62$ $p.Eta^2=0.003$
	Med (2.5–3)	148	108.9 ± 82.7	94.0 ± 202.3			
	High (> 3)	121	146.2 ± 91.3	136.3 ± 223.2			
Parental support: instrumental	Low (< 2.5)	62	67.4 ± 61.6	45.6 ± 156.1	$F_{1,298}=2.27$ $p=0.13$ $p.Eta^2=0.010$	$F_{2,298}=14.5$ $p<0.01$ $p.Eta^2=0.089$	$F_{2,298}=1.55$ $p=0.21$ $p.Eta^2=0.010$
	Med (2.5–3)	112	125.3 ± 94.2	82.5 ± 179.1			
	High (> 3)	127	142.8 ± 83.7	148.8 ± 232.0			
Parental support: companion	Low (< 2.5)	52	99.1 ± 79.0	67.3 ± 178.2	$F_{1,300}=2.78$ $p=0.10$ $p.Eta^2=0.009$	$F_{2,302}=4.06$ $p=0.02$ $p.Eta^2=0.026$	$F_{2,300}=0.50$ $p=0.61$ $p.Eta^2=0.003$
	Med (2.5–3)	182	113.1 ± 75.3	106.2 ± 204.9			
	High (> 3)	69	157.6 ± 113.8	125.2 ± 216.7			
Siblings	Active	168	126.7 ± 91.9	117.2 ± 217.9	$F_{1,301}=0.85$ $p=0.36$ $p.Eta^2=0.003$	$F_{2,301}=3.64$ $p=0.03$ $p.Eta^2=0.024$	$F_{2,301}=1.99$ $p=0.14$ $p.Eta^2=0.013$
	Not active	83	109.3 ± 89.6	58.7 ± 129.5			
	No siblings	53	115.8 ± 73.5	137.9 ± 239.7			
Family SES	Low (< 9)	35	119.9 ± 120.8	82.9 ± 168.0	$F_{1,295}=1.62$ $p=0.20$ $p.Eta^2=0.005$	$F_{2,295}=0.56$ $p=0.57$ $p.Eta^2=0.004$	$F_{2,295}=0,21$ $p=0.81$ $p.Eta^2=0.001$
	Med (9–17)	219	116.5 ± 81.9	104.9 ± 203.5			
	High (> 17)	44	135.7 ± 96.9	119.2 ± 234.0			
Garden ownership	No	45	124.5 ± 87.9	85.2 ± 145.5	$F_{1,305}=2.18$ $p=0.14$ $p.Eta^2=0.007$	$F_{1,305}=0.20$ $p=0.66$ $p.Eta^2=0.001$	$F_{1,305}=0.64$ $p=0.43$ $p.Eta^2=0.002$
	Yes	262	118.9 ± 88.4	107.2 ± 211.1			

M mean; *SD* standard deviation

Table 3 shows the factors influencing playing outside. There was a significant main effect for time indicating a significant increase of minutes per day playing outside ($F_{1,313}=49.7$; $p<0.01$; $p.Eta^2=0.137$). This did not differ between boys and girls. Siblings did not influence the minutes per day playing outside in preschool children. In contrast to emotional, informational, and instrumental support, parental companionship showed a time-stable positive effect on playing outside ($F_{2,309}=3.15$, $p=0.04$, $p.Eta^2=0.020$). Furthermore, having an own garden indicated a significant interaction effect with time and playing outside. Descriptive statistics revealed a larger increase in playing outside during the lockdown among preschool children who live in a house or apartment with a garden ($F_{1,313}=5.51$, $p=0.02$, $p.Eta^2=0.017$).

Table 4 shows that leisure ST increased from pre to peri the lockdown in preschool children ($F_{1,314=}204.5$; $p<0.01$; $p.Eta^2=0.394$) with no main effect for gender. Furthermore, it can be seen that socioeconomic status ($F_{2,304}=3.20$, $p=0.04$, $p.Eta^2=0.021$) as well as having an own garden ($F_{1,314}=3.88$, $p=0.05$, $p.Eta^2=0.012$) had an influence on leisure ST in preschool children. Descriptive data indicated higher amounts of screen time with lower SES and not having an own garden. A small interaction effect can be seen for parental companionship ($F_{2,309}=3.11$, $p=0.04$, $p.Eta^2=0.020$).

Discussion

The aim of the present study was to investigate the influence of the family environment, specifically SES, parental support, garden ownership, and having siblings on COVID-19-related changes in PA and ST behavior in German preschool children using longitudinal data.

Our results show a non-significant decline in the total amount of sports-related PA in preschool children from pre to during the first lockdown of the COVID-19 pandemic. The non-significance could be explained by the great variance in preschool children with some children having 0 min of the total amount of sports-related PA per week while other preschool children reached 1000 min per week and

Table 3 Factors influencing playing outside in 4–5 old children before and during the COVID-19 lockdown in Germany (MoMo Study)

Playing outside [minutes per day]							
Age 4–5 years	Descriptives				rmANOVA		
Factor	Value	n	Pre (M ± SD)	Peri (M ± SD)	Time	Factor	Time*factor
Gender	Boys	169	92.4 ± 57.3	131.8 ± 104.9	$F_{1,313}=49.7$ $p<0.01$ $p.Eta^2=0.137$	$F_{1,313}=0.65$ $p=0.42$ $p.Eta^2=0.002$	$F_{1,313}=0.31$ $p=0.58$ $p.Eta^2=0.001$
	Girls	146	83.3 ± 58.1	129.5 ± 96.6			
Parental support: emotional	Low (< 2.5)	36	97.4 ± 60.1	142.8 ± 116.3	$F_{1,311}=35.7$ $p<0.01$ $p.Eta^2=0.103$	$F_{2,311}=1.28$ $p=0.28$ $p.Eta^2=0.008$	$F_{2,311}=0.39$ $p=0.68$ $p.Eta^2=0.002$
	Med (2.5–3)	159	85.5 ± 60.4	123.4 ± 92.7			
	High (> 3)	119	88.8 ± 53.7	138.0 ± 106.2			
Parental support: informational	Low (< 2.5)	35	83.8 ± 56.9	127.0 ± 101.5	$F_{1,309}=33.6$ $p<0.01$ $p.Eta^2=0.098$	$F_{2,309}=0.07$ $p=0.93$ $p.Eta^2=0.000$	$F_{2,309}=0.12$ $p=0.89$ $p.Eta^2=0.001$
	Med (2.5–3)	152	86.3 ± 60.5	131.8 ± 97.6			
	High (> 3)	125	90.2 ± 54.4	129.6 ± 100.7			
Parental support: instrumental	Low (< 2.5)	62	92.2 ± 73.3	131.2 ± 96.2	$F_{1,307}=41.6$ $p<0.01$ $p.Eta^2=0.119$	$F_{2,307}=0.41$ $p=0.67$ $p.Eta^2=0.003$	$F_{2,307}=0.05$ $p=0.96$ $p.Eta^2=0.000$
	Med (2.5–3)	114	84.3 ± 51.6	125.5 ± 104.9			
	High (> 3)	134	89.4 ± 55.3	133.1 ± 95.5			
Parental support: companion	Low (< 2.5)	53	70.9 ± 54.0	116.6 ± 90.5	$F_{1,309}=41.6$ $p<0.01$ $p.Eta^2=0.119$	$F_{2,309}=3.15$ $p=0.04$ $p.Eta^2=0.020$	$F_{2,309}=0.34$ $p=0.71$ $p.Eta^2=0.002$
	Med (2.5–3)	186	89.5 ± 58.0	128.0 ± 94.6			
	High (> 3)	73	96.1 ± 58.1	146.2 ± 114.4			
Siblings	Active	172	87.0 ± 55.5	134.7 ± 101.1	$F_{1,309}=37.1$ $p<0.01$ $p.Eta^2=0.107$	$F_{2,309}=0.17$ $p=0.84$ $p.Eta^2=0.001$	$F_{2,309}=0.72$ $p=0.49$ $p.Eta^2=0.005$
	Not active	85	93.3 ± 68.3	124.2 ± 97.6			
	No siblings	55	82.6 ± 47.6	127.9 ± 107.3			
Family SES	Low (< 9)	36	80.1 ± 54.8	144.1 ± 95.2	$F_{1,303}=28.7$ $p<0.01$ $p.Eta^2=0.086$	$F_{2,303}=0.12$ $p=0.88$ $p.Eta^2=0.001$	$F_{2,303}=1.05$ $p=0.35$ $p.Eta^2=0.007$
	Med (9–17)	225	87.8 ± 57.4	130.0 ± 101.7			
	High (> 17)	45	99.0 ± 63.5	131.4 ± 102.0			
Garden ownership	No	47	90.1 ± 62.4	99.0 ± 105.2	$F_{1,313}=11.6$ $p<0.01$ $p.Eta^2=0.036$	$F_{1,313}=3.20$ $p=0.07$ $p.Eta^2=0.010$	$F_{2,313}=5.51$ $p=0.02$ $p.Eta^2=0.017$
	Yes	268	87.8 ± 57.0	136.3 ± 99.3			

M mean; *SD* standard deviation

Table 4 Factors influencing leisure screen-time in 4–5 old children before and during the COVID-19 lockdown in Germany (MoMo Study)

Leisure screen-time [minutes per day]							
Age 4–5 years	Descriptives				rmANOVA		
factor	value	*n*	Pre (M ± SD)	Peri (M ± SD)	Time	Factor	Time*factor
Gender	Boys	170	52.7 ± 47.8	97.4 ± 64.8	$F_{1,314=}204.5$ $p<0.01$ $p.Eta^2=0.394$	$F_{1,314}=0.65$ $p=0.80$ $p.Eta^2=0.003$	$F_{1,314}=1.79$ $p=0.18$ $p.Eta^2=0.006$
	Girls	146	51.4 ± 47.7	88.4 ± 64.2			
Parental support: emotional	Low (< 2.5)	36	63.1 ± 73.8	99.3 ± 63.5	$F_{1,311}=131$ $p<0.01$ $p.Eta^2=0.296$	$F_{2,311}=0.81$ $p=00.44$ $p.Eta^2=0.002$	$F_{2,311}=0.35$ $p=0.71$ $p.Eta^2=0.002$
	Med (2.5–3)	159	53.5 ± 44.2	93.6 ± 63.1			
	High (> 3)	119	47.3 ± 42.0	91.0 ± 67.6			
Parental support: informational	Low (< 2.5)	35	58.6 ± 40.6	97.7 ± 51.3	$F_{1,309}=136$ $p<0.01$ $p.Eta^2=0.305$	$F_{2,309}=0.26$ $p=0.77$ $p.Eta^2=0.002$	$F_{2,309}=1.08$ $p=0.34$ $p.Eta^2=0.007$
	Med (2.5–3)	152	52.6 ± 54.5	90.1 ± 66.5			
	High (> 3)	125	50.3 ± 40.7	96.6 ± 66.1			
Parental support: instrumental	Low (< 2.5)	63	55.9 ± 53.3	87.5 ± 65.3	$F_{1,307}=170$ $p<0.01$ $p.Eta^2=0.357$	$F_{2,307}=1.95$ $p=0.16$ $p.Eta^2=0.012$	$F_{2,307}=1.68$ $p=0.19$ $p.Eta^2=0.011$
	Med (2.5–3)	114	57.0 ± 54.1	103.1 ± 69.0			
	High (> 3)	133	46.8 ± 38.6	88.4 ± 60.6			
Parental support: companion	Low (< 2.5)	53	63.8 ± 66.4	91.1 ± 64.0	$F_{1,309}=128$ $p<0.01$ $p.Eta^2=0.293$	$F_{2,309}=1.70$ $p=0.19$ $p.Eta^2=0.011$	$F_{2,309}=3.11$ $p=0.05$ $p.Eta^2=0.020$
	Med (2.5–3)	186	52.3 ± 45.3	98.6 ± 68.5			
	High (> 3)	73	44.5 ± 35.8	82.4 ± 54.3			
Siblings	Active	172	47.9 ± 44.3	89.9 ± 59.5	$F_{1,310}=171$ $p<0.01$ $p.Eta^2=0.355$	$F_{310}=1.08$ $p=0.34$ $p.Eta^2=0.007$	$F_{2,310}=0.28$ $p=0.76$ $p.Eta^2=0.002$
	Not active	85	57.8 ± 52.5	95.6 ± 65.1			
	No siblings	56	56.5 ± 50.0	100.1 ± 77.5			
Family SES	Low (< 9)	36	73.1 ± 63.8	110.9 ± 70.1	$F_{1,304}=115$ $p<0.01$ $p.Eta^2=0.274$	$F_{2,304}=3.20$ $p=0.04$ $p.Eta^2=0.021$	$F_{2,304}=0.60$ $p=0.55$ $p.Eta^2=0.004$
	Med (9–17)	225	49.6 ± 45.8	88.7 ± 61.8			
	High (> 17)	46	48.1 ± 40.3	96.8 ± 68.5			
Garden ownership	No	47	64.6 ± 78.6	107.6 ± 75.9	$F_{1,314}=109$ $p<0.01$ $p.Eta^2=0.258$	$F_{314}=3.98$ $p=0.05$ $p.Eta^2=0.012$	$F_{1,314}=0.08$ $p=0.78$ $p.Eta^2=0.000$
	Yes	269	49.9 ± 39.7	90.7 ± 62.2			

M mean; *SD* standard deviation

more. Overall, during the first lockdown, restrictions like the closure of sports clubs, preschools as well as contact restrictions had a large impact on everybody's daily life and one's opportunities for being active. Other studies investigating PA levels in preschool children also indicated a decrease in the total amount of sports-related PA (Aguilar-Farias et al., 2020; Carroll et al., 2020; Clarke et al., 2021; Guan et al., 2020; Jauregui et al., 2021; Kracht et al., 2021) and thus, confirmed our descriptive findings of decreasing total amounts of sports-related PA, even if data did not reach statistical significance. However, a study from Sweden found increases in PA levels in preschool children (Delisle Nystrom et al., 2020). Contrary to the other countries, Sweden did not close preschools, parks, or playgrounds, and organized sports continued. These findings from different countries highlighted the importance of preschools, playgrounds, and sports clubs for the accumulation of PA levels throughout the day.

We extended our study by focusing on different social influencing factors on the change of the total amount of sports-related PA in preschool children as especially for younger children families and their support seem to be associated with PA levels in preschool children as parents are the gatekeeper for PA (Bingham et al., 2016; Gariguett et al., 2017; Hinkley et al., 2008; Loprinzi et al., 2010; Mitchell et al., 2012; Schmutz et al., 2017). In this context, our data indicated an influence of parental support on preschool children's total amount of sport-related PA. Our descriptive data, that did not reach statistical significance, indicated that more parental support is associated with higher amounts of total sports activity pre-lockdown, and preschool children's sports levels during the lockdown did not strongly change when they received more parental support. Due to the closure of preschools during the pandemic, preschool children require larger parental support which may mean managing and supervising children's activities and behaviors was more challenging for these families, particularly if parents were working (Prime et al., 2020). In this context, an existing qualitative study concluded that parental support for children's PA during the pandemic was easier when one parent was not working and therefore, these children accumulated higher PA levels (Clarke et al., 2021; Pombo et al., 2020). Another explanation that should be taken into account refers to the function of modeling. PA levels in children can depend on the activity level of their parents as they play an important role as health behavior models (Sigmund et al., 2008).

Furthermore, the amount of sports-related PA in preschool children differed depending on having a(n) (active) sibling. Our data described statistically significant differences with the highest levels of sports in preschool children having an active sibling while having an inactive sibling is associated with the lowest levels of sports activity. Regarding the descriptive, not reaching statistical significance data, it can be seen that before lockdown, active siblings play fewer minutes outside with their siblings compared to non-active siblings (87.0 ± 55.5 vs. 93.3 ± 68.3). This could be explained by active siblings engaging more time in organized sports compared to playing with their siblings. During the lockdown no organized PA was allowed and active siblings could then be more engage in playing outside with their siblings (see Table 3). Existing COVID-19 literature showed that having someone to play with in times of restrictions, especially siblings, increases the likelihood to be physically active and thus, these children were significantly more active during the lockdown than children without siblings (Aguilar-Farias et al., 2020; Clarke et al., 2021; Jauregui et al., 2021; Pombo et al., 2020). Nevertheless, even if our data did not reach statistical significance, it seems important that the sibling is active too. Otherwise, PA levels decreased. Furthermore, having no sibling seems to be associated with a higher total amount of sports activity during the lockdown. This is slightly different from other studies indicating that children with siblings were more active during the lockdown than children without siblings (Aguilar-Farias et al., 2020; Clarke et al., 2021; Jauregui et al., 2021; Pombo et al., 2020). Nevertheless, these differences should be interpreted with caution because existing studies did not differentiate between active or inactive siblings.

Furthermore, the MoMo-PA questionnaire differentiates between different types of PA and therefore, we were able to analyze outdoor play separately. Our data indicated a significant increase in outdoor play across 4–5-year-olds in Germany with no differences between boys and girls. Non-essential institutions and sports clubs were closed (Press and Information Office of the Federal Government, 2020b), so children had more recreational time to engage in outdoor play during the lockdown. Data from the US highlighted the relevance of outdoor play during COVID-19 lockdown to stay physically active (Dunton et al., 2020). Studies from other countries revealed decreases in PA that can be explained by different policy restrictions. During the lockdown in China, for example, outdoor activities were not allowed (Chen et al., 2020). Similar results were seen in Spain where leaving the house was only allowed for work, grocery shopping, or doctor's visit (Guan et al., 2020). In Sweden, the preschools remained open, and outdoor activities were allowed, so children showed an increase in time spent outdoors on weekdays as well as weekend days. Additionally, Swedish preschools changed their routines to have their children outside as much as possible (Delisle Nystrom et al., 2020). These examples support the assumption of a relationship between policy restrictions and outdoor play levels during pandemic (Beck et al., 2021).

Our data indicate significant differences in the levels of outdoor play between children receiving different levels of companionship from their parents. The increase in levels of outdoor play was greater in children whose parents often accompany their preschool children in their activities than in preschool children with less companionship support, as could be seen in the descriptive data. These not reaching statistical significance findings could be explained by the need for parental supervision and companionship for outdoor play in preschool children (Tandon et al., 2012a, 2012b). Furthermore, an interaction effect between an own garden and the lockdown related to outdoor play was significant. The results indicate a larger increase in preschool children who have access to their own garden. Due to the closure of recreational playgrounds, access to an own garden provides the opportunity for playing outside and this represents one of the strongest predictors for PA during the lockdown (Aguilar-Farias et al., 2020; Schmidt et al., 2021). In England, a qualitative study supported the importance of outdoor space for preschool children's PA levels. Parents with no outdoor space described this as quite challenging: *'We couldn't leave and there was nothing really you could do. And living in a block of flats, you can't be too noisy because you've got neighbours everywhere.'* (Clarke et al., 2021). These data demonstrated that having access to outdoor space is an important predictor for outdoor play and thus, PA levels in preschool children.

Complementary to a decrease in the total amount of sports-related PA, our data revealed a significant increase in leisure ST in preschool boys and girls from pre to during the lockdown in Germany. This finding is confirmed by further studies across various countries (Aguilar-Farias et al., 2020; Jauregui et al., 2021; Kracht et al., 2021; Lopez-Bueno et al., 2020). In particular, Lopez-Bueno et al. (2020) reported an increase of 132 min per day of screen exposure in Spanish 3–5-year-old children, and, preschool children in Chile doubled their ST during the lockdown (Aguilar-Farias et al., 2020). With higher time spent at home due to the restrictions, it was expected that screen exposure could reach higher levels than before the COVID-19 confinement. In this context, the COVID-19 pandemic has imposed digital platforms as this was the only mean to stay in contact with other people (Pandya & Lodha, 2021). Furthermore, the WHO stated to stay active by engaging in online sports offers or active video games (World Health Organization, 2020). This needs to be considered when interpreting the increasing ST in preschool children. Nevertheless, the SES as well as having an own garden seems to be associated with the change in ST. Our descriptive data revealed that the great differences in ST between low, medium, and high SES before the lockdown were getting smaller during the lockdown, even if the interaction effect doesn't reach statistical significance. This is in line with another study indicating that especially preschool children from higher educated parents spent much time engaging in screen time during the lockdown because these parents had to work from home more frequently (Aguilar-Farias et al., 2020). This is interesting as, before the pandemic, children with more educated caregivers tended to engage with less time with screen-based devices. This may be partially explained as more educated caregivers may have to work from home, and this, in turn, may require the caregiver to use screens to entertain their child while working from home (Aguilar-Farias et al., 2020). Furthermore, higher income and thus higher SES is affected with garden ownership (Al-Dala'een, 2017). Our descriptive, not statistical significant results showed that preschool children living in an apartment or house with an own garden had lower levels of ST pre and during the lockdown. These children had more opportunities to spend recreational time outside and thus, less need to engage in ST (Clarke et al., 2021).

Undoubtedly, parental support as well as having active siblings play a key role in facilitating movement behaviors of preschoolers as we can see in our data. Nevertheless, some political actions during lockdowns may boost the process. Our findings reinforce the need for ensuring an activity-friendly environment for children at home and in surrounding areas to play. This is likely to promote these behaviors not only during the pandemic but also in the return to a "new normal" throughout all socioeconomic classes (Aguilar-Farias et al., 2020; Schmidt et al., 2021). Thus, decision-makers should seek options to facilitate outdoor recreational activities while preserving safety and physical distancing instructions. Furthermore, specific content for promoting PA through social media and national TV as a response to the pandemic could be installed as it was done in particular in Chile (Elige Vivir Sano Ministerio de Desarrollo Social y Familia Gobierno de Chile 2022).

Limitations

Despite the comprehensive and longitudinal approach to investigating PA in preschool children during the COVID-19 lockdown in Germany, there are some limitations to our study. First, the representativeness of our longitudinal sample is limited because of the unforeseen lockdown during the collection of the pre-study sample which resulted in an interruption of the field research. Furthermore, the preliminary response rate of 25% also affected the representativeness of the present study. Second, the results of PA in Germany within the MoMo-Study are based on self-reports, respectively for preschool children, parents fulfilled the questionnaire (proxy-report). This could limit the validity of the answers as parents act as mediators and especially related to the social support scales answers could be influenced by social expectations. Furthermore, non-literary parents had problems to help their children at all. Nevertheless, the used questionnaire assessed different settings and types of PA and featured a higher focus on recall bias compared to unspecific questionnaires used in other studies (Delisle Nystrom et al., 2020; Lopez-Bueno et al., 2020). Third, as the present study is a natural experiment there is no control group and we can only assume that the changes in PA were caused by the lockdown. Due to the fact that we analyze longitudinal data from 4 to 5-year-olds before the lockdown and a full representative capture of Germany takes two years in our design, the mean age for the second measurement point during the lockdown exceeded the mean age pre-lockdown by almost exactly one year. Lastly, an increase in outdoor play can be explained by the weather during the COVID-19 lockdown and the questionnaire in April 2020 in Germany. It was untypically warm with a mean temperature of 10.4 °C (9.6 °C in 2019) and on average 292.4 sunshine hours (227.9 in 2019) (German Weather Service, 2019, 2020) which could have influenced the outdoor activities of children and their families.

Conclusion

The results of the current study revealed that during the COVID-19 lockdown, the total amount of sports activity decreased while outdoor play, as well as recreational ST, increased in preschool children in Germany. Furthermore, our data indicated that especially for doing sports parental support and siblings seem to be important predictors for preschool children. In addition to this, the physical environment like having an own garden can positively influence health-related behaviors, especially outdoor play and ST in preschool children. To provide every child with PA opportunities during potential future lockdowns, restriction policies should be adapted and parents need sophisticated information about the importance of their support and thus the PA levels of their children.

Authors' contribution Conceptualization: Franziska Beck, Steffen C. E. Schmidt, Alexander Woll, Anne K. Reimers; Methodology: Franziska Beck, Steffen C. E. Schmidt, Anne K. Reimers; Formal analysis and investigation: Steffen C. E. Schmidt; Writing – original draft preparation: Franziska Beck: Writing – review and editing: Franziska Beck, Steffen C. E. Schmidt, Alexander Woll, Anne K. Reimers; Funding

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Declarations

Conflict of interest Franziska Beck has declared no conflicts of interests. Steffen C. E. Schmidt has declared no conflicts of interests. Alexander Woll has declared no conflicts of interests. Anne K. Reimers has declared no conflicts of interests.

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Ethical approval This study was approved by Charité Universitätsmedizin Berlin ethics committee (Baseline Study), by the University of Konstanz (Wave 1), and the ethics committee of the Karlsruhe Institute of Technology (Wave 2 and 3, a positive ethics vote was given from on 23 September 2014 by the ethics committee of the KIT).

Human and animal rights The study was conducted in accordance with the Declaration of Helsinki. No animals or humans were harmed during the course of the study.

Informed consent Parents gave their written consent for minors and the presence of a legal guardian was mandatory under the age of 15. Participation in the study was voluntary and every participant received a gift worth 20 €. The participants or their custodians were informed about the contents of the study and about data protection and gave their written consent.

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Summary

This study should exemplarily show how variability occurred and how preschool children handled such perturbations that are followed by a deviation from the habitual PA behavior. Our results indicate a decline in total amount of sports-related PA, an increase in outdoor play, as well as an increase in leisure screen time in preschool children during the Covid-19 pandemic (respectively because of the restrictions and measures). However, having a deeper look at the results, the changes in total amount of PA varied between children with different levels of parental support as well as in dependence on having siblings. Even if preschool children had a lack of activity due to closure of sports clubs and kindergarten, children receiving higher parental support seemed to compensate this loss by being active at home (supported by their parents). Furthermore, levels of outdoor play and screen time in preschool children were influenced by environmental factors like having access to their own garden. This data highlighted that the social and physical environment can help to compensate decreases of PA in other domains due to restrictions. We conclude that the family environment (parental support as well as physical environment) is highly relevant for PA and screen time levels in preschool children. Besides this, it confirmed the previous studies regarding the importance of social support to maintain a stable PA level, even if there are external factors that unbalance the habitual behavior of children and adolescents.

Implication

Summarizing the findings from both articles using subjective measurement methods, this approach helps to understand compensation more holistically. Especially as subjective measurement methods are able to provide insights into occurrence and perception of activity compensation, as well as the setting and influencing factors, we gained a deeper understanding of compensatory behavior in adolescents. Combining device-based and subjective measurement tools may be the most advantages approach to assess compensatory behavior in children and adolescents.

5 General Discussion and Future Directions

Little knowledge about variability and stability in the context of PA existed in the public health research. Thus, investigating variability and stability as well as gaining information about activity compensation in childhood and adolescence was the main topic of the dissertation.

5.1 Current Status of Variability of Physical Activity in Children and Adolescents

In general, various factors seem to have an influence on PA behavior (McLeroy et al., 1988) and these factors could act like perturbations in one's habitual behavior, resulting in variability of PA in everybody's daily life. Based on the socioecological model of McLeroy et al. (1988) five levels were identified and the impact of these are explored in various studies. In our study focusing on family predictors of PA changes during the pandemic, we identified differences in PA levels on the interpersonal level, namely depending on social support of parents and siblings (Beck et al., 2022c) (see also chapter 5.2.2). This is in line with other studies focusing on interpersonal level. Receiving higher social support is associated with higher PA levels in children and adolescents (Kwon & O'Neill, 2020; Reimers et al., 2019; Rhodes et al., 2020). Furthermore, in our rapid review as well as within the MoMo-study we focused on the impact of changes within the policy level (Beck et al., 2022c; Beck et al., 2022d). The Covid-19 pandemic is characterized by several restrictions and measures leading to drastic changes in public and personal life (Press and Information Office of the Federal Government, 2020b). Furthermore, these changes brought changes to the population's PA and lifestyle behavior. The included studies showed a predominantly decline of PA levels, which is also confirmed in other studies (Brand et al., 2022; Park et al., 2022; Stockwell et al., 2021; Wunsch et al., 2021). In addition, much is already known about the variability on the intrapersonal level. For instance, it is indicated that PA levels decline with increasing age, lower SES, or higher weight status (Andersen & Bakken, 2019; Gomes et al., 2017; Rittsteiger et al., 2021; Vollmer et al., 2019; Woll et al., 2019). Summarizing, these data indicate that a change in one's PA affecting determinants leads to changes and thus variability of PA behavior in children and adolescents.

5.2 Current Status of Activity Compensation in Children and Adolescents

Compensatory responses to perturbations like changes within the social and physical environment in PA may negate desirable intervention or in a more general way, health effects. As such, being able to predict those who may compensate based on their perceptions may be critical for health and activity promotion and strategies to minimize compensatory responses. Thus, the existing findings concerning prevalence and mechanisms, respectively the influencing factors of activity compensation in children and adolescents should be discussed in more detail.

5.2.1 Prevalence of Compensation

Overall, with our conducted studies we could neither confirm nor reject the existence of an ActivityStat, but it seems that there is a complex interaction between biological control and further influencing factors that could affect the prevalence of compensation (see chapters 4.2.1 and 5.1.2). The systematic review included in the thesis was the first of its kind to summarize activity compensation in children and adolescents across all studies using device-based measurement methods on an international level (Beck et al., 2022b). Overall, the systematic review highlights that there is a lack of purpose-designed studies and consistent methodology in assessing or identifying compensatory responses. A total of 77 articles were included that investigated compensation across various contexts in children and adolescents. Overall, approximately 50% of the included articles found indicators suggesting compensation, and 50% refuted activity compensation in children and adolescents (Beck et al., 2022b). Furthermore, the studies conducted within the cumulative dissertation also confirmed the inconclusive findings of the review regarding prevalence of activity compensation in children and adolescents (Beck et al., 2022b). The secondary data analysis revealed compensatory behavior in 60% of observation points within (pre)adolescents girls (Beck et al., 2022a). Beck et al. (2024) focused on perception and mechanisms of compensatory behavior in adolescents, and still investigated the prevalence of compensation. The 15 participating adolescents accumulated 198 opportunities to compensate over one week of which 109 were actually compensated, resulting in a prevalence of 55.1% (Beck et al., 2024). Other reviews confirmed the inconclusive results regarding the existence of an ActivityStat and whether compensatory behavior in children and adolescents occurs (Gomersall et al., 2013; Swelam et al., 2022).

Direction of Compensation

Activity compensation is defined as increases/decreases at one timepoint that are followed by decreases/increases at another timepoint (Gomersall et al., 2013). Thus, as this definition states, activity compensation can occur in two opposite directions. To distinguish between these two, we call an increase after a decrease as a positive/healthful compensation, whereas decreasing activity after an increase is connotated as negative because the more of activity does not lead to an increase of the overall PA levels due to compensatory behavior afterwards.

Overall, the studies conducted within the thesis indicate that the direction of compensatory response is predominantly negative (Beck et al., 2022a; Beck et al., 2022b), however, depending on the study design, differences can be seen (Beck et al., 2024): In general, the direction of compensatory behavior has been investigated for the first time within our systematic review (Beck et al., 2022b), however within the review, only one study was able to report on a positive compensation, where girls having lower PA levels in school increased their PA levels out of school (Tudor-Locke et al., 2006). Another study that was published after acceptance of the review focused on German children and indicated higher MVPA levels than usual the day after higher than usual SB levels were noted (Nigg et al., 2022). Until then the direction of activity compensation was still quite unexplored. Our study based on secondary data analysis was able to add more knowledge on this research field as we analyzed each girl separately and were able to indicate that all girls with low SB levels (indicating higher PA levels) in the morning or on weekdays, compensated for this behavior with lower PA levels in the afternoon or on weekends (Beck et al., 2022a). Regarding the prevalence of positive and negative compensation within the qualitative study (Beck et al., 2024), the tendency towards higher negative compensation could be confirmed as we found slightly more negative compensation compared to positive compensation (52.2% vs. 47.8%). This difference to the other study could be explained as the compensatory behavior was assessed by subjective measurement methods that are known for recall bias and social desirability (Corder et al., 2008).

Ratio of Compensation

The data from the previous studies indicated that at least 50% of children and adolescents appeared to compensate their activity to some ratio after a perturbation (Beck et al., 2022a; Beck et al., 2022b; Beck et al., 2024), suggesting that researchers can anticipate a certain level of compensatory reaction to an intervention designed to enhance overall activity. As it is not expectable that the exact amount of deviation would be compensated, compensation was classified as low (0-49.9%), medium (50.0-74.9%) or high (74.0-99.9%) partial compensation as well as overcompensation (>100%). Beck et al. (2024) focused on the ratio of compensation and the results showed quite heterogenous results ranging from 4% to 2173% of compensation. Overall, descriptive data showed that especially low amounts of deviation were overcompensated, and that high amounts of deviation had only low partial compensatory responses. We could assume two potential reasons for the heterogenous results regarding the ratio of compensatory response. One reason could be enjoyment of PA as this seems to influence the ratio of compensation (Swelam et al., 2023b). For example, children would compensate an increase of PA levels by 80% when they did not enjoy the activity versus only a small partial compensation of < 50% when they enjoyed the additional activity (influence of enjoyment on activity compensation can be seen in chapter 4.2.1 and 5.2.2) (Swelam, 2022).

Besides the enjoyment of activity, the intensity could also be a decisive factor for the ratio of compensatory response. Swelam (2022) found that perturbations in LPA may trigger less compensatory responses (e.g., low partial compensation or no compensation). Hence, it is worth to explore the possibility that incorporating LPA (such as standing lessons) into a child's school day could effectively result in prolonged enhancements in children's activity levels (Verswijveren et al., 2022). Advancing the ActivityStat hypothesis (Rowland, 1998), incorporating LPA into a school day might lead to diminished compensatory responses compared to activities of higher intensity. Consequently, forthcoming research should explore the implications of these findings for the integration of such insights into school activity programs.

Timespan of Potential Compensatory Responses

Regarding the timespan of compensation synthesized by the three main articles focusing exclusively on compensatory behavior (Beck et al., 2022a; Beck et al., 2022b; Beck et al., 2024), there is no conclusive result that could determine when compensation occurs. Following the systematic review (Beck et al., 2022b) activity compensation occurred mainly between-day. Nevertheless, our empirical studies indicated that more than half of the compensatory situations took place within-day (Beck et al., 2022a; Beck et al., 2024). This was also stated in the study of Swelam et al. (2023b), who postulated that compensation scarcely occurred between-days because starting a new day could function as a kind of reset. Even if the findings from our systematic review are line with Gomersall et al. (2013) stating that it is unlikely that an ActivityStat would occur within hours or a single day, these findings need to be limited/discussed. The predominance of between-day compensation identified in our systematic review could also be explained by a greater number of included between-day studies compared to within-day studies (Beck et al., 2022b).

In summary, there is no conclusive results concerning the timespan of potential compensatory responses. Information about the timespan of compensatory responses is still necessary as this is from practical relevance, as it will direct methodological choices regarding design, frequency of measurement and the duration of the intervention.

5.2.2 Influencing Factors of Activity Compensation

Given the complexity of the topic, including how little is currently understood about activity compensation, our data indicated inconclusive results concerning compensation prevalence. Within the thesis, influencing factors should be identified to explain the inconsistency of the occurrence of compensatory behavior. The following paragraph will focus and discuss therefore identified reasons or influencing factors for compensatory behavior.

Within our systematic review, we could not identify any influence of sociodemographic factors on compensatory behavior across the few studies that took these factors into account (Beck et al., 2022b). Regarding age as one potential influencing factor, our empirical studies included in the dissertation focused on preschool children (Beck et al., 2022c) as well as on (pre)adolescent girls (Beck et al., 2022a; Beck et al., 2024). Across all these studies, compensatory behavior was identified, thus, indicating that compensatory behavior occurs across all age spans. In terms of sex/gender differences, our systematic review revealed compensatory behavior in boys and girls (Beck et al., 2022b), even there are few included studies supporting compensation only in girls and not in boys (Cooper et al., 2003; Schneller et al., 2017; Tudor-Locke et al., 2006). However, the tendency of no sex/gender differences is confirmed in the qualitative study (Beck et al., 2024). Further we could not identify any association between compensation and weight status or SES (Beck et al., 2022a).

These findings are in line with the few existing studies that focused on different age groups (Gidlow et al., 2008; Long et al., 2013; Nigg et al., 2022) with compensatory behavior across all age spans from preschool children (Alhassan et al., 2012) to adolescents (Kek et al., 2019b; Nigg et al., 2022). Further, Swelam et al. (2023a) focused on elementary school children which emphasizes this point. Same can be seen for gender with studies indicating compensatory responses in boys and girls (Alderman et al., 2012; Cooper et al., 2003; Jago et al., 2014; Long et al., 2013; Nigg et al., 2022; Tudor-Locke et al., 2006).

However, compensatory findings in terms of sociodemographic data are in contrast to PA levels as sociodemographic data (SES, age, weight status) is in general associated with PA levels of children and adolescents (Andersen & Bakken, 2019; Gomes et al., 2017; Rittsteiger et al., 2021; Vollmer et al., 2019; Woll et al., 2019).

In summary it is possible, that such findings, including consistent compensatory behavior across sociodemographic groups, may be indicative of a biological compensatory set-point and degree of tolerance (Gomersall et al., 2013; Rowland, 1998).

Nevertheless, as inconclusive results regarding the prevalence of compensation exist (Beck et al., 2022a; Beck et al., 2022b; Gomersall et al., 2013; Swelam et al., 2022), we assume that the biological control is influenced by other factors than sociodemographic data that could explain the inconsistency.
In terms of negative compensation, an important influence for adolescents to reduce their PA levels after an increase is that they feel exhausted and tired, so they rest and do not continue with their habitual PA behavior (Beck et al., 2024). This was also confirmed in elementary school children, where children as well as their parents mentioned an overall sense of tiredness or sore muscles as a way that compensatory response to increased activity may manifest (Swelam et al., 2023b). Regarding an interventional study, 18% of adolescents reported that they were too tired to be active after school when they had standing lessons at school before (Bronwyn et al., 2016). Thus, it seems that the duration and intensity level of interventions need to be under a certain threshold that leads to tiredness and over-exhaustion. Otherwise, it is likely that compensation occurs and thus, the overall level of PA does not increase.

A further factor influencing compensatory response seems to be the social support, including peers' and parental companionship as well as instrumental, informative and emotional support (Pyper et al., 2016; Uchino, 2004). Children predominantly mentioned that their PA behavior depends on the availability of friends to participate in sports together, especially to continue with the habitual behavior after an increase of PA. Nevertheless, if there is a lack of social support, the probability to compensate an increase with a subsequent decrease is high (Beck et al., 2024). Social support is not only helpful to avoid negative compensation, but can also help to support positive compensation (Beck et al., 2024). Family and friends could then help to be active after a restriction of PA levels. The importance of social support could also be seen during the Covid-19 pandemic (Beck et al., 2022c), while daily (active) life was restricted by various measures (Press and Information Office of the Federal Government, 2020a). Overall, the findings of this study underpin the influence of social support identified within the qualitative study (Beck et al., 2024). In particular, data indicated that higher parental support is associated with higher amounts of total sports activity pre-lockdown, and further, preschool children's sports levels and outdoor play during the lockdown did not strongly change when they received higher parental support, even if a lot of restrictions concerning PA behavior existed (e.g., organized sports and preschools were closed). Furthermore, the amount of sports-related PA in preschool children differed depending on having a(n) (active) sibling. Our data described statistically significant differences, as preschool children with an active sibling tend to show the highest levels of sports, having an inactive sibling is associated with the lowest levels of sports activity. Thus, it seems that the social support of active siblings helps to compensate the lack of activity due to the closure of organized sports (Beck et al., 2022c). Ascribing social support great importance in terms of compensatory behavior is also confirmed in the study of Swelam et al. (2023b) with "[…] children who had siblings or parents that would engage in physical activities together reported this as something that might keep them active, regardless of having had an active day at school" (p. 8). Furthermore, previous literature has highlighted the importance of familial co-participation and social support as facilitators of PA (Beets et al., 2010; Biddle et al., 2011). Therefore, providing children with opportunities to still be active after increases of PA or providing an active home environment (i.e., social support, opportunities for family/siblings/peers co-participation) may reduce potential compensatory responses to an active day.

Routines, including (self-) obligatory activities, were also identified as an influence with positive impact on compensatory behavior (Beck et al., 2024). In this context, children mentioned interrelated mechanisms, such as the child's after school routine (e.g., organized sport), as factors that would keep a child active and may prevent them from having a compensatory response to higher than usual levels of activity in a day (Beck et al., 2024; Swelam et al., 2023b).

In addition, enjoyment might be a factor that is responsible for self-obligatory activities. Enjoyment in activities helps on the one hand to stay active after increases of PA levels and, on the other hand, can motivate children to be more active due to a preceded reduction of activity (Beck et al., 2024). Enjoyment is also responsible for the ratio of compensation (see *Ratio of compensation*). This finding of enjoyment of PA resulting in less compensation was already seen in our review which noted that compensation was not observed in non-interventional studies, assuming that children did not compensate for activities they chose to participate in and that intrinsic motivation for an activity could outweigh compensatory responses (Beck et al., 2022b). Thus, this kind of 'hedonistic activities' seem to override the biological control and may subsequently result in less negative compensatory behavior, especially in the instance of habitual hedonistic activities (Rowland, 2016).

Another influencing factor that should be discussed in more detail is weather. In general, it is known that weather is one of the strongest predictors of PA (Duncan et al., 2008; Harrison et al., 2017). Having this in mind, it is not surprising that compensation is also influenced by the weather condition. Within the interviews, adolescents reported that their preceded lack of activity was compensated by more activity than usual especially when the weather is good (e.g., sun is shining, it's not too hot, …). In contrast, it was mentioned that bad weather hinders them to be (more) active than usual as they do not see any possibilities to be active indoor (Beck et al., 2024; Swelam et al., 2023b). Thus, there is a need to show adolescents how to be active indoors (see chapter 5.4.2).

5.2.3 Existence of an ActivityStat

The ActivityStat is thought to influence activity via a neuro-humoral feedback loop of the central nervous system, operating in unremitting cycles dictated by muscle tissue receptors, and the hypothalamus-based (the region of the brain responsible for other homeostatic mechanisms such as fluid balance, temperature, and caloric intake) activity set-point (Wilkin et al., 2006). The primary objective of the ActivityStat is to ensure that activity output matches its set-point (Wilkin, 2011).

In the following, the results of the present thesis should be transferred to the concept of an ActivityStat that is under biological control. Overall, we identified activity compensation in children and adolescents. Nevertheless, as the prevalence of activity compensation is inconsistent, the findings assume that there exists an ActivityStat, with compensatory mechanisms being consistent with traditional PA and SB correlates (e.g., sociodemographic data). Our results indicated consistent compensatory behavior across sociodemographic groups, that may be indicative of a biological control of PA behavior (Gomersall et al., 2013; Rowland, 1998). However, as there are inconsistent results concerning the occurrence of compensation, it seems that the biological control is somehow malleable as the ActivityStat, respectively the compensatory response can somehow be influenced by several factors like the social and physical environment. Factors that were identified act therefore as supporters of positive compensation or preventers of negative compensation.

Further, a central component of the functionality and elasticity of the ActivityStat is the activity tolerance that is oriented to an innate set-point value. Within the thesis, we could not answer this question, but gained first insights. To address this, there exist several approaches, following the same core concept. The studies within the thesis were non-experimental studies and focused on the habitual and cross-sectional PA behavior of children and adolescents. Deviations, no matter whether increases or decreases of PA, were identified by focusing on the individual variability of PA (Eisenmann & Wickel, 2009), and subsequent compensation was identified. For the purpose of the studies within the thesis, this was done by ensuring on the one hand that the difference in activity between morning and afternoon as well as weekdays and weekend days is at least ±1.645 standard deviation (Beck et al., 2022a), and on the other hand that the deviation of MET-minutes was at least ±20% different from the corresponding time period within the habitual activity schedule (Beck et al., 2024). However, not all existing studies assessed the amount of deviation even if this is necessary to firstly assess if this is outside of the normal intra-individual variability (Eisenmann & Wickel, 2009) and secondly, to determine the ratio of compensation.

To determine one's variability within seven days, this could also be done by completing a habitual PA measurement over one week, given the suggested seven-day periodicity of activity in previous research (Rowlands et al., 2015), and not just asking the subjects about a typical weekly schedule as this is susceptible for recall bias and social desirability (as it was done in Beck et al. (2024)). Thus, the degree to which a child's PA fluctuates from their mean PA across days, using for example Coefficient of Variation (Eisenmann & Wickel, 2009), could be calculated and give information about variability of activity behavior. In this context, studies should also contain an appropriate length of data collection to detect compensation, although the timespan at which compensation occurs is still unknown (Rowlands, 2009).

In terms of the set-point it should shortly be discussed if this set-point is innate or adjustable. As Swelam (2022) found that perturbations in LPA may result in less compensatory responses, incorporating LPA into a child's school day has the potential to increase children's activity levels prolonged (Verswijveren et al., 2022) (see chapter 5.2.2). This potential outcome could arise as the set-point of the ActivityStat undergoes a shift or modulation (Wilkin, 2011), demonstrating an increased tolerance to higher activity levels before triggering compensatory reactions. In other words, the ActivityStat may be a gradual response (i.e., the imposition or restriction of higher activity intensities are required to activate a compensatory response) and may therefore be less reactive to lower levels of increased energy expenditure resulting from a perturbation (Swelam, 2022).

5.3 Challenges of Identification and Assessment of Compensatory Behavior

The previous chapter summarized and discussed the findings of the thesis concerning compensatory behavior of children and adolescents based on the ActivityStat hypothesis. In this context, various challenges of identification and assessment of activity compensation were figured out.

First of all, before compensatory behavior could be assessed, there is a need to define compensation. Currently, there remains still a lack of consensus regarding the best definition of compensation, what amount of compensation is truly considered compensation (e.g., 50%, 75%, etc.), whether the term 'activity' compensation adequately encompasses the full scope of an ActivityStat, and whether compensation may be beneficial (positive) or harmful (negative) for health.

It is crucial to emphasize that not all forms of compensation are inherently 'harmful' or negative, in fact, some compensation may assist children in maintaining their regular PA levels over time, particularly when compensating for a decrease in PA. While compensation of reduced PA levels and consequently, additional sedentary time, may be considered 'healthful' or positive, conversely, compensation of additional PA could, to an extent, be considered 'harmful' in instances where the intention is to increase PA (e.g., in interventions). This is particularly significant given the well-established mental, physical, and social benefits associated with elevated levels of PA in children (Poitras et al., 2016).

Nevertheless, while adhering to the recommended PA guidelines would be considered optimal (Aubert et al., 2022; Burchartz et al., 2021; Guthold et al., 2020), it is essential to also contemplate situations where negative activity compensation might be necessary. For example, activity compensation is hypothesized to be a biological function, and the findings in this thesis (chapter 4.2.1) noted physiological factors such as the management of fatigue as a factor in compensatory responses with reasons such as overexertion, sore muscles, or an overall sense of tiredness mentioned by children. This suggests that in some instances, there may be a biological need for compensation, or that the body may signal the need for this type of beneficial PA compensation (Swelam, 2022).

As soon as there is a clear understanding about the definition of compensation, further challenging points should be considered. Based on how the ActivityStat is hypothesized to function (e.g., operating around a set-point and having a degree of tolerance), it is thought that there are several important methodological functions that must be undertaken to accurately measure compensation. In this context, the results within the thesis found that compensation occurs in more than half of possible opportunities (e.g., deviation from the habitual behavior greater than ±20%) (Beck et al., 2022a; Beck et al., 2024) which was both contrasted as well as supported by previous literature (Beck et al., 2022b; Gomersall et al., 2013; Swelam et al., 2022). However, such comparisons to other compensatory literature should be interpreted with caution given the findings of systematic reviews, which illustrated the inconsistent methodologies used in assessing compensation and the challenges in determining whether compensation occurred (Beck et al., 2022b; Rowland, 2016; Swelam et al., 2022).

In particular, different approaches were applied within existing studies that assessed compensatory behavior. Most of the existing compensation studies investigated compensatory behavior by using the mean values of all participants within the study and thus only obtained one value for all participants and for each timespan (Adkins et al., 2013; Aljuhani & Sandercock, 2019; Groffik et al., 2020; Kidokoro et al., 2019; Stylianou et al., 2016). Even if Nigg et al. (2022) also took the individual mean values of every individual for compensation analysis into account, the result of the multilevel analysis indicated one mean value under consideration of all participants' individual means. Thus, within the studies in the present thesis, we analyzed each individual separately, and even various observation points/opportunities within one subject to get information about each individual resulting in more comprehensive results (Beck et al., 2022a; Beck et al., 2024). Furthermore, in this context, various studies analyzed compensatory behavior by comparing two (or more) groups, especially within intervention studies (Alhassan et al., 2018; Alhassan et al., 2007; Coombes & Jones, 2016; Cooper et al., 2003; Magnusson et al., 2011; Mallam et al., 2003; Pesola et al., 2018), instead of focusing on within subject compensatory behavior, that is more informative than doing a between subject analysis as compensation concerns the individual. This is also supported by our study in which multilevel covariate analysis indicated great variability between the participants (Beck et al., 2022a). The challenge for detecting and analyzing compensation is to develop a study design that makes within subject analysis possible. In this context, to control for compensatory behavior, experimental conditions can be implemented to guarantee same conditions for all participants that make a comparison easier. Experimental research could include the imposition or restriction of activity behavior during times that would normally be active/inactive and ensuring that the perturbation is sufficiently outside of individual's variability (Eisenmann & Wickel, 2009).

As different measurement methods have different advantages and disadvantages (chapter 4.1. and 4.2), the most appropriate approach needs to be identified. In this context, Rowlands (2009) stated that measurement tools should also be able to detect small changes, as the longer the timescale, the smaller the changes may be. When eliciting compensatory responses, the increased and/or decreased activity should be outside of the daily variability threshold (±20-25%) and thus, measurement methods should be able to detect variability (Rowlands, 2009). Reviews indicated a wide range of measurement methods including subjective and device-based approaches (Beck et al., 2022b; Gomersall et al., 2013; Swelam et al., 2022). Researcher should verify that all measurement tools are tailored to the specific outcome of interest, such as the prevalence of compensatory behavior, timespan of compensatory responses, or influencing factors for compensation. Specifically, using device-based measurement tools, it is crucial to assess 24-hour movement behavior, encompassing sleep time, as compensation could also occur by going to bed earlier following an increase of PA levels. To assess PA and compensatory behavior in a quantifiable way, it is necessary to use device-based measurement methods like accelerometers. With our calibration and validation study (see chapter 4.1.1), we provided an accelerometer with determined cut-off points for children aged 8-13 years (Beck et al., 2023). Previously, cut-off points for children's activities were based on typical adult cut-off points (Sallis et al., 1991). Nevertheless, due to different body structures (i.e., weight, leg length, height) and locomotion, (e.g. how many steps are taken within a given epoch length) this is not appropriate (Sallis et al., 1991). As such, the use of adult cut-off points on children results in an observed systematic underestimation of activity, ranging from 5-40% (Sallis et al., 1991). Following, it was recommended that age-specific cut-points are used to mitigate this risk (Migueles et al., 2017). This may then help to appropriately investigate the PA behavior (deviation and compensation) in children and (pre)adolescents and further to gain information about timespan and ratio of compensation. However, device-based measurement methods are unable to assess the perception of compensation and potential influencing factors. To assess these variables, subjective measurement methods are needed as these are able to establish the mode, setting, and/or context of which activity takes place, along with the perception associated with activity behavior (Corder et al., 2008; Trost et al., 2000). Adding subjective measurement methods may help to holistically illustrate and investigate compensatory behavior. In our qualitative study we used an activity diary and interview to get more information about the activity itself as well as about the situation in which the activity occurs (e.g., weather, companionship, mood before and after …). This data will be analyzed soon. Nevertheless, adolescents often forgot to track their activities or did not answer all questions.

5.4 Future Directions

In the previous chapter, challenges and methodological considerations around activity compensation were addressed and may give important implications for future research and practical implications.

5.4.1 Future Research Directions

In general, it is necessary for future research aiming to assess compensation, to be purpose-designed and to have a clear understanding of methodological implications (Rowland, 2016). For this, is it helpful to have a clear and common understanding of what compensatory behavior is and how to define it (see chapter 5.2). However, we identified further research directions that should be discussed in more detail.

For instance, compensatory behavior needs to be assessed in an appropriate way. Within the thesis, different measurement approaches were conducted. While no measurement tool is perfectly suited to assess all components of PA, combining several tools, using a mixed methods approach, allows researchers a more comprehensive access to children's activity, context of the activity, and perceptions around activity and/or behaviors (Corder et al., 2008; Dollman et al., 2009). In many cases it is recommended to utilize both a device-based measure, such as accelerometry, to provide accurate quantifiable data, and complement it with self-reported qualitative data to provide insights into the context (Dollman et al., 2009). In this context, ambulatory assessment may be a good way to investigate and understand compensatory behavior in a holistic way. Ambulatory assessment involves employing field methods to evaluate the real-time behavior, physiology, experiences, and environmental factors of individuals in natural or unrestricted settings. Utilizing ecologically valid tools, ambulatory assessment aims to comprehend biopsychosocial processes as they naturally occur over time and within specific contexts (Fahrenberg et al., 2007; Reichert et al., 2020; Trull & Ebner-Priemer, 2013). The calibrated and validated sensor within the thesis (Chapter 4.1.1) from Movisens GmbH can be used as an ambulatory assessment tool. By connecting the sensor with a smartphone app, this enables a unique capability to trigger questionnaires when they matter most (e.g., questions about perception, context and setting of PA and feeling during activity).

When implementing experimental conditions to assess compensation, an alternative strategy for gaining a more profound understanding of the mechanisms underlying compensation (at the time of compensation) involves conducting qualitative interviews post-experiment. Thereby, the completed usual compensation measures serve as an interview prompt, aiming to better understand what children think after compensating (e.g., was that their normal behavior, is the observed response typical for them), and how they compensated (if at all), in the context of the experimental condition. Extending the scope to include parents and/or teachers in these interviews can provide additional insights into children's behavior, recognizing the value of proxy-reported data, especially in younger children (Swelam, 2022). Swelam et al. (2023b) were the first to develop a specific survey to explore the perception of compensation, as well as factors that may influence compensatory responses in children and adolescents. However, some of the additional scales were not reliable, leaving an opportunity for future researchers to develop additional purpose designed subscales. Another potential technique involves participatory approaches, like the use of write and draw methods, which can be employed to extract additional qualitative insights from children in a more interactive way (Knowles et al., 2013).

In the context of data collection, future research should consider exploring compensatory responses in specific population sub-groups, and approaches such as sensitivity analyses to understand if and how compensation occurs differently across different groups.

Additionally, future studies should consider that meteorological data during the whole PA measurement period are collected. As seen in Chapter 4.2.1, we identified weather as an important influencing factor for compensatory behavior. Future studies should subsequently control for weather effects in the analysis.

A further important research implication concerns compensation as being a ‘trait’ or a ‘state’. While there seems to be a degree of malleability (Rowland, 1998, 2016) in the ActivityStat, suggesting that it can be influenced and potentially altered by social, environmental, and interpersonal factors, the extent of their impact on compensatory responses remains uncertain. As such, this leaves the question of whether compensation occurs as a ‘trait’ (i.e., whether a child is consistently a ‘compensator’ or ‘non-compensator’) or ‘state’ (i.e., compensatory responses are situational) (Chaplin et al., 1988). In this context, as our qualitative study analyzed compensatory behavior over one week focusing on various settings, we gained first insights about compensation being a ‘trait’ or a ‘state’. Analyzes over one week indicated that adolescents did not compensate all of their compensatory opportunities and thus, it is suggested that compensation is more a ‘state’ than a stable personal ‘trait’ (Beck et al., 2024). Nevertheless, future research should be conducted to challenge this tendency. Especially, there is a need to explore compensatory responses across multiple settings (i.e., school, home, organized sport, etc.), time periods (i.e., before school, after school, on the weekend, etc.), and experimental conditions (i.e., imposed activity, restricted activity) using device-based and subjective measurement methods to determine whether compensation occurs as a ‘trait’ or a ‘state’.

Besides the assessment and analysis of compensation, there are suggestions future interventional studies should consider. First of all, data indicates that negative compensation occurs because of tiredness and over-exhaustion (Beck et al., 2024). Thus, it seems that the duration and intensity level of interventions need to be under a threshold that leads to tiredness and over-exhaustion.
In addition, future research might explore the effectiveness of a comprehensive, multicomponent school-based activity interventions. This might involve programs that provide parents and after-school providers with tools and resources to encourage active participation, thereby nurturing the development of after-school community playgroups and other extracurricular activities (Swelam, 2022).

5.4.2 Practical Implications

The findings of this thesis suggest that more than half of children and adolescents compensate their movement behaviors to some ratio and that compensation may be the result of biological control that is further influenced by various internal and external factors (e.g., environmental, interpersonal, psychological, and physiological factors). As such, there are several opportunities for parents and children themselves, schools, and after-school care providers to assist in mitigating children’s and adolescents’ compensatory responses.

Firstly, in general, social support has an important influence on PA in children and adolescents (Beets et al., 2010; Gustafson & Rhodes, 2006; Sallis et al., 2000). The importance of social support was also seen in compensatory analysis as family and friends could avoid negative compensation or support children and adolescents to compensate a preceded decrease of PA (see Chapter 4.2.1) (Beck et al., 2022c; Beck et al., 2024; Swelam et al., 2023b). Parents should aim to model healthy activity behaviors. Specifically, parents can create various active opportunities before and after school (such as utilizing active transport where feasible) and on weekends, ideally engaging together with the family (Sallis et al., 2000). Furthermore, parents can seek guidance on how to address situations where compensation is anticipated, along with solutions to encourage or facilitate compensatory responses (Swelam, 2022).

For adolescents, the role of peers is getting more important than parental support and social support from peers is also associated with higher activity levels (Sawka et al., 2013). Regarding compensation, we could also identify a positive impact of friends/peers. In particular, regular and habitual PA is maintained after an increase of PA, when the habitual PA is performed with friends. Furthermore, friends help to compensate a lack of PA by being more active together and motivate each other (Beck et al., 2024; Swelam et al., 2023b). Thus, it is helpful to have active friends.

Family and friends can also be supportive in maintaining routines. Routines were identified as an influencing factor for compensation (Beck et al., 2024; Swelam et al., 2023b). In this context, routines may also be important in avoiding negative compensation as adolescents wanted to stick to their routines. As such, further support for adolescents in finding active routines is needed. For instance, if a parent knows that a child has had an active day, they could encourage their child to maintain their usual PA routine after school (e.g. organized sports) (Mooses & Kull, 2019).

Closely linked to routines is the fact, that enjoyment supports the PA behavior of children and adolescents. Thus, it is important that adolescents find activities they like, as such 'hedonistic activities' seem to override the biological control and may subsequently result in less negative compensatory behavior, especially in the instance of habitual hedonistic activities (Rowland, 2016). This could also be part of an intervention: Interventions should then prioritize assisting children in discovering their preferred activities and offer suggestions to parents on how to support and foster these interests as they evolve. Including such 'hedonistic activities' into daily life helps to be physically active even if an increased PA was preceded (Chapter 4.2.1 gives implication for research in this context) (Swelam, 2022).

Furthermore, an awareness of health benefits may be an important factor to support positive and avoid negative compensation. This was also identified in the qualitative study (Beck et al., 2024), where adolescents having a greater health awareness compensated more positive and less negative compared to adolescents with a lower health awareness. To achieve knowledge about the benefits of PA, parents need to be provided education in this direction (De Meester et al., 2014). Once there is awareness in this domain, parents have the opportunity to educate their children about the significance of staying active and foster a sense of self-awareness regarding their activity levels. Increased levels of both self-efficacy and awareness may enhance a child's engagement in PA (Chase, 2001; Salmon et al., 2009). For instance, parents might offer and promote the adoption of wearable technology, such as smartwatches, to enhance their child's awareness of and motivation for PA (Creaser et al., 2021; Koorts et al., 2020). However, the responsibility for promoting awareness of health benefits should not solely rest on parents; schools can also contribute by addressing this matter within and across various classes, such as PE lesson and biology.

In general, research has suggested that schools are an important setting for PA (World Health Organization, 2018a). Our studies identified that a lot of compensation occurred in the afternoon after school, this may suggest that schools are a setting that provides children and adolescents appropriate opportunities to be active. As such, schools could introduce novel active opportunities and programs aiming to increase intrinsic motivation and adherence (Lakicevic et al., 2020). These initiatives could incrementally raise in- and out of school PA levels, including after school programs. By progressively increasing in-school PA opportunities, this approach may assist children with limited after-school PA in increasing their overall daily PA levels. Simultaneously, it may help mitigate negative compensatory responses to increased PA levels by operating within the tolerance window and subsequently modulating PA (Beets et al., 2016). Moreover, novel active opportunities could increase the intrinsic motivation and the feeling of joy of movement that could lead to a higher after-school PA and thus, this may be beneficial for positive compensation, respectively for avoiding negative compensation (see Chapter 4.2.1). Considering that a child's environment and interpersonal factors influence compensatory responses (Beck et al., 2024; Swelam et al., 2023b), schools might also contemplate keeping their facilities open or permitting equipment use after school.

Further, weather was identified as one important influence for compensatory behavior. Good weather seems to support positive compensation whereas bad weather seems to support negative compensation. Therefore, understanding indoor activities is crucial. Parents might observe restlessness in a child on days when outdoor activities are canceled due to unfavorable weather conditions, resulting in missed opportunities for activity. As a solution, parents could promote children or engage with them in indoor games such as active screen use (e.g., Dance Dance Revolution, Wii, etc.) (Sweetser et al., 2012), allowing children to remain active within the confines of their home. Furthermore, schools should aim to provide opportunities for PA when recess and lunchtime breaks are spent inside due to wet weather or excessive heat (Swelam, 2022).

In summary, the previous chapter highlighted various research gaps that should be addressed in future research while simultaneously having the challenges and methodological considerations in mind. Nevertheless, there could already be identified a lot of practical implications taking different environments (school, friends, family) into account to avoid negative and support positive compensation.

5.5 Methodological Limitations of the Current Investigations

This cumulative dissertation steps into the investigation of variability and stability of PA behavior in children and adolescents as an important source to promote PA in a sufficient and effective way. Despite efforts to gather the best evidence to describe compensatory behavior in children and adolescents, this dissertation project has some limitations.

Firstly, the generalizability of results of the systematic review is limited due to the methodological approach. The heterogeneity of study designs and methodology within the included studies made a comparison of the results difficult. Comparison was also limited by the various used indicators or measures for activity behavior. Additionally, some studies only allowed between-subject analyses, which, in turn, only enabled conclusions about compensation to be obtained from a comparison of PA levels between two groups (Beck et al., 2022b).

Additionally, our qualitative study showed also some limitations (Beck et al., 2024). Overall, we excluded adolescents without a smartphone due to the smartphone-based assessment. Furthermore, the habitual weekly schedule was self-reported and occurred as a once-off assessment by asking the adolescents to provide a schedule over one week instead of assessing habitual behavior across several weeks. As such, this could be associated with social desirability by indicating more active behaviors than usual. Same can be transferred to the PA assessment over one week via self-report, which also carries the risk for recall bias.

Overall, the systematic review highlighted the complexity of measuring the compensatory behavior of children and adolescents (Beck et al., 2022b). Thus, in the empirical studies conducted within the thesis, we tried to find suitable approaches to assess compensation. Nevertheless, our studies showed limitations that should be considered in future research. For instance, in our secondary data analysis, we did not analyze different segments during the school day to acquire more information about PA behavior during school hours, like recess, lunch breaks, etc. Furthermore, we did not consider further factors like seasonal or meteorological variability (Beck et al., 2022a). The importance of the weather was in fact identified in our qualitative study (Beck et al., 2024). Thus, considering the weather would have been important to confirm the results of the qualitative study.

Related to the analysis of compensation, we utilized a ±20% deviation (or ±1.645 standard deviation) from the habitual PA behavior as a threshold for intra-individual variability, however this threshold could be to high (Ridley et al., 2009) or to low (Rowlands et al., 2015) and an assessment of variability would have been better. Furthermore, given the complexity of the topic, including how little is currently understood about activity compensation, and with a clear relationship between external factors and the biological mechanism, it was not possible to explore all potential avenues of movement behavior compensation. Especially the lack of knowledge and instruments that should be used to assess compensatory behavior in a holistic way made it difficult to classify the results in existing research findings.

5.6 Conclusion

The findings in this thesis provide novel insights into variability and stability of PA in children and adolescents. Specifically, compensatory behavior in children and adolescents was investigated by using different approaches, offering valuable knowledge for national and international researchers and practitioners striving to combat the global issue of physical inactivity by gaining a deeper understanding of PA behavior.

In order to gain these insights, various research approaches like a systematic review, secondary data analysis and qualitative interviews were implemented to investigate variability and stability of PA in children and adolescents. Various factors were determined as perturbators that may lead to variability of activity levels. Nevertheless, as the ActivityStat hypothesis postulates a stable activity level, activity compensation was investigated with device-based and subjective measurement methods. Next to the prevalence (including timespan and ratio), also the perception and influencing factors of activity compensation were focused within the studies.

Overall, the findings assume that there exists an ActivityStat, as children do compensate their activity, regardless of demographic differences; however inconsistent findings concerning prevalence of compensation could be identified. Thus, it seems that the biological control, like other homeostatic mechanism (Rowland, 1998), is somehow malleable. In more detail, the ActivityStat, respectively the compensatory response, is influenced by several factors like the social and physical environment.

The thesis has highlighted challenges in identification and assessment of compensatory behavior with a focus on appropriate measurement methods. Especially a combination of device-based (like for children and adolescents calibrated and validated accelerometers) and subjective measurement methods (diaries, interviews) may be appropriate to assess compensation in a holistic and comprehensive way. However, further considerations must be given to movement behavior compensation in the design and evaluation of PA promoting strategies, and the perception of compensation may provide critical insights into potential compensatory responses. This will be critical for the development and evaluation of future interventions that aim to increase children's PA and decrease SB. Lastly, the thesis provides first practical implications to avoid negative and support positive compensation in children and adolescents. In particular, social support seems to facilitate positive compensation, whilst routines and hedonistic activities may assist in avoiding negative compensatory behavior. Thus, it seems to be helpful to support individuals in their search for hedonistic activities as well as in the establishment of routines.

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