Mood-enhancing Physical Activity in Individuals with Attention-Deficit/Hyperactivity Disorder (ADHD) and Healthy Youths
– Daily Life Investigations by Ambulatory Assessment

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Summary

Physical activity is a central parameter for preventing disease in healthy individuals and for improving physical and mental health. Regarding mental health, evidence exists that improving co-occurring symptoms of a disorder may also improve a disorder's main symptoms. For example, as studies have shown that negative affect and impulsivity are related to each other, chances are high that improving the outcome of the main symptom (e.g., impulsivity) of a mental disorder (e.g., ADHD) can be achieved by improving its co-occurrent symptom (e.g., negative affect).

These symptoms, feelings, and behaviors (e.g., physical activity) fluctuate enormously within individuals over time and may be related to each other. Studies investigating fluctuating parameters and dynamic processes, which may provide a holistic explanation of how different variables wax and wane within a person over time, have recently increased in number, which has been enabled by technical progress made in the fields of activity tracking and smartphone technologies. With the Ambulatory Assessment method (i.e., measuring using electronic-diaries (e-diaries) and accelerometers), investigating these dynamic processes in real time and in individuals' everyday life has become feasible, simpler, and less burdensome.

The main goals of this work were to investigate associations between physical activity and mood in a community-based adolescent sample and in individuals with ADHD, as well as in a sample of healthy controls. Hence, we examined how these dynamic variables fluctuate over time and how they are related to each other. In addition, a review provides an overview of e-diary studies in ADHD research (i.e., a state-of-the-art review), summarizing the state-of-the-art and future prospects for how ADHD research could be improved by technical progress made in Ambulatory Assessment.

In the first paper, the association between mood and subsequent incidental physical activity was investigated in the everyday life of a community-based adolescent sample (N=113) between twelve and seventeen years of age. The participants were monitored using the Ambulatory Assessment method (i.e., e-diaries and accelerometers) over one week. The results showed that in adolescents, the mood dimensions of 'valence', 'energetic arousal', and 'calmness' were related to subsequent incidental physical activity (e.g., climbing stairs, walking the dog). Specifically, the mood dimensions of 'valence' and 'energetic arousal' were positively, and 'calmness' was negatively, related to subsequent incidental physical activity. These findings suggest that mood can be an antecedent that drives physical activity in healthy adolescents.

In the second paper, the same community-based adolescent sample (N=113) was used. Herein, the analysis was changed to determine whether mood could be seen solely as an antecedent driving physical activity or whether there is evidence that physical activity also drives subsequent mood as a consequence. In addition, the study considered whether the type of physical activity had an influence on the mood dimensions ‘valence’, ‘energetic arousal’, and ‘calmness’ and divided physical activity into three categories (i.e., incidental physical activity, exercise, and sports). The results showed that physical activity was to be related to subsequent mood in healthy adolescents. Regarding the mood dimensions and physical activity categories in detail, healthy adolescents felt better and more energized after incidental physical activity (e.g., climbing stairs); they felt better but less calm after exercise (e.g., skating); and they felt less energized after sports (e.g., playing tennis). These results suggest that in healthy adolescents, mood is not only an antecedent but also a consequence of physical activity.

The third paper represents a review summarizing the state-of-the-art e-diary studies in ADHD research. Twenty studies with children and adolescents, as well as thirteen studies with adults, showed that Ambulatory Assessment is a helpful method by which to understand dynamic patterns in ADHD that cannot be investigated in physicians’ offices, laboratories, or clinical settings. Furthermore, Ambulatory Assessment can support psychiatric practice by revealing fluctuations over time that could be relevant in a clinical context and, hence, could improve diagnosis (i.e., digital phenotyping).

In the fourth paper, individuals with ADHD (n=143) and healthy controls (n=42) were studied for four days using e-diaries and accelerometers to determine whether physical activity was related to subsequent mood. The individuals with ADHD were exploratively divided into two groups (i.e., Group 1, those who were predominantly inattentive (n=48); and Group 2, those with a combined presentation of symptoms (n=95); i.e., both inattentive and hyperactive). The results showed physical activity to be related to subsequent affect in individuals with ADHD, depending partly on their predominant symptoms. Specifically, positive affect was improved by physical activity in each of the three groups (i.e., 1. the predominantly inattentive; 2. those with combined presentation; and 3. healthy controls), whereas negative affect was improved by physical activity only in the subsample that was more hyperactive than others (i.e., Group 2). Hence, the hypothesis that physical activity is significantly related to subsequent positive affect in individuals with ADHD can be confirmed. However, for negative affect, the hypothesis that physical activity is significantly related to subsequent negative affect can only be confirmed for the individuals with ADHD who are more hyperactive than the others.

The final chapter summarizes the limitations and lessons learned from prior Ambulatory Assessment studies in this field, as well as from our studies, to suggest implications for future investigations. Prior Ambulatory Assessment studies investigating physical activity and mood showed limitations, such as missing control groups, the use of self-report assessments instead of objective approaches for measuring physical activity. Furthermore, studies rarely focused on the parameterization of the type of exercise and intensity thresholds, how successful an exercise was (e.g., winning or losing a game), or the specification of mood dimensions. Further, the general discussion provides an overview of mobile health (mHealth) components that were used in the different trials described in this work and especially focuses on their technical and methodological innovations. On that basis, implications for technical and methodological requirements are described that should be focused on in future Ambulatory Assessment studies. Additionally, this chapter shows which components and features of the Ambulatory Assessment method are already implemented in supporting diagnoses in clinical practice in the sense of digital phenotyping. Cognitive tasks assessed by smartphones, such as an objective measurement for impulsivity (i.e., assessed with the stop-signal task) or working memory (i.e., assessed with the spatial n-back or memory-updating task), are considered here. Furthermore, how movement patterns from accelerometers could be used as digital markers to further identify symptomatology in mental disorders are discussed. It may be that there are microspectra in movement patterns that differ significantly in individuals with ADHD compared to healthy individuals. Finding such digital markers (e.g., for hyperactivity) could support the diagnosis of mental disorders and hence improve clinical practice.

Zusammenfassung

Körperliche Aktivität ist ein wichtiger Bestandteil zur Prävention von Erkrankungen bei gesunden Menschen, sowie auch zur Gesundheitsförderung bei physischen und psychischen Erkrankungen. Bei letzterem besteht dahingehend Evidenz, dass eine Milderung der Begleiterscheinungen einer psychischen Erkrankung mit einer Verbesserung des eigentlichen Krankheitsbildes, das heißt der Hauptsymptome, einhergehen könnte. Studien belegen beispielsweise einen signifikanten Zusammenhang zwischen negativem Affekt, als häufig auftretende Begleiterscheinung bei psychischen Erkrankungen, und Impulsivität, als eines der Hauptsymptome der Aufmerksamkeitsdefizit-/Hyperaktivitätsstörung (ADHS). Somit wird vermutet, dass eine Verbesserung von negativem Affekt auch gleichzeitig Impulsivität positiv beeinflussen könnte.

Diese genannten Symptome, Gefühle, aber auch Verhaltensweisen, wie beispielsweise körperliche Aktivität, fluktuieren stark innerhalb von Personen über die Zeit und weisen untereinander möglicherweise Zusammenhänge auf. Durch Ambulantes Assessment und wachsendem technischem Fortschritt werden zunehmend einfachere und weniger beschwerliche Möglichkeiten geboten diese dynamischen Prozesse im Alltag adäquat abzubilden und zu untersuchen. Ambulantes Assessment beschreibt dabei das Untersuchen von Personen in ihrem Alltag in Echtzeit mit beispielsweise elektronischen Tagebüchern und Akzelerometern.

Die Hauptziele dieser Arbeit fokussieren sich auf die Zusammenhänge zwischen körperlicher Aktivität und Stimmung bei Jugendlichen und ADHS PatientInnen, sowie gesunden Kontrollen. Dabei wird untersucht, wie diese von Natur aus dynamischen Variablen über die Zeit zusammenhängen bzw. sich gegenseitig bedingen. Zusätzlich wird eine Übersichtsarbeit (Review) zum Thema „elektronische Tagebücher in der ADHS-Forschung“ vorgestellt, die den Stand der Forschung, sowie Zukunftsperspektiven zur Verbesserung der ADHS-Forschung, durch stetig wachsenden technischen Fortschritt im Ambulanten Assessment, darlegt.

Im ersten der vier Paper dieser Arbeit wurden Jugendliche, zwischen zwölf und siebzehn Jahren, einer willkürlich ausgewählten gemeindenahen Stichprobe (N=113), in ihrem alltäglichen Leben, hinsichtlich des Zusammenhangs zwischen Stimmung und nachfolgender spontaner körperlicher Aktivität, untersucht. Über einen Zeitraum von einer Woche wurden sie durch Ambulantes Assessment (d.h. mit elektronischen Tagebüchern und Akzelerometern) begleitet. Die Ergebnisse zeigen einen Effekt der Stimmungsparameter ‚gute Stimmung‘, ‚Wachheit‘ und ‚Ruhe‘ auf alltägliche spontane körperliche Aktivität (z.B. Treppensteigen) bei Jugendlichen. Im Detail ergab sich ein positiver Zusammenhang zwischen den Stimmungsparametern ‚gute Stimmung‘ und ‚spontaner körperlicher Aktivität‘ sowie auch zwischen ‚Wachheit‘ und ‚spontaner körperlicher Aktivität‘. Zwischen den Variablen ‚Ruhe‘ und

‚spontaner körperlicher Aktivität' zeigte sich hingegen ein negativer Zusammenhang. Diese Ergebnisse deuten darauf hin, dass Stimmung einen Effekt auf nachfolgende spontane körperliche Aktivität bei Jugendlichen aufweist.

Im zweiten Paper wurde dieselbe Stichprobe analysiert (d.h. Jugendliche einer willkürlich ausgewählten gemeindenahen Stichprobe; N=113). Hier wurde im Gegensatz zum ersten Paper der Fokus darauf gelegt, ob Stimmung auch eine Konsequenz aus körperlicher Aktivität sein könnte, d.h. ob Stimmung von vorausgehender körperlicher Aktivität beeinflusst werden könnte. Ein weiterer Schwerpunkt befasste sich mit der Frage, ob die Art der körperlichen Aktivität (d.h. alltägliche spontane körperliche Aktivität, sportliche Freizeit-Aktivität, oder Wettkampfsport) differenzielle Effekte auf die Stimmungsparameter ‚gute Stimmung', ‚Wachheit' und ‚Ruhe' zeigen. Bei differenzierter Betrachtung der Art der körperlichen Aktivität und der drei Stimmungsparameter zeigte sich, dass sich die Jugendlichen besser gelaunt und energiegeladener nach alltäglicher spontaner körperlicher Aktivität (z.B. mit dem Hund spazieren gehen), besser gelaunt aber unruhiger nach sportlicher Freizeit-Aktivität (z.B. Skaten) und weniger energiegeladen nach Wettkampfsportarten (z.B. Tennis) fühlten. Diese Ergebnisse deuten darauf hin, dass Stimmung nicht nur körperliche Aktivität bedingt, sondern umgekehrt auch körperliche Aktivität die Stimmung beeinflussen kann.

Die dritte Publikation in dieser Arbeit ist eine Übersichtsarbeit (Review), die den Stand der Forschung zu elektronischen Tagebuchstudien in der ADHS-Forschung zusammenfasst. Zwanzig Studien mit Kindern und Jugendlichen, sowie dreizehn Studien mit Erwachsenen legen nahe, dass Ambulantes Assessment eine hilfreiche Methode ist, um dynamische Prozesse in ADHS abzubilden, die nicht in der Sprechstunde, im Labor, oder im klinischen Setting erhoben werden können. Ambulantes Assessment kann die psychiatrische Praxis durch die Untersuchung dieser dynamischen Prozesse, die im klinischen Kontext von Bedeutung sein könnten, unterstützen, und somit möglicherweise auf digitalem Wege Diagnosen untermauern (durch die sogenannte „digitale Phänotypisierung").

Im vierten Paper wurden ADHS PatientInnen (n=143) und gesunde Kontrollen (n=42) über vier Tage mit elektronischen Tagebüchern und Akzelerometern untersucht, um herauszufinden, ob auch bei dieser klinischen Stichprobe Stimmung von vorausgehender körperlicher Aktivität beeinflusst wird. Die ADHS PatientInnen wurden dabei explorativ in zwei Gruppen unterteilt: 1. prädominant unaufmerksam (n=48) und 2. sowohl unaufmerksam als auch hyperaktiv (n=95). Die Ergebnisse zeigen, dass körperliche Aktivität mit nachfolgender Stimmung bei ADHS PatientInnen, abhängig von ihren prädominanten Symptomen, zusammenhängt. Im Detail konnte körperliche Aktivität positiven Affekt in allen Gruppen (1. ADHS prädominant unaufmerksam; 2. ADHS unaufmerksam und hyperaktiv; 3. gesunde Kontrollen) verbessern, wohingegen körperliche Aktivität negativen Affekt nur bei der Teil-Stichprobe, die hyperaktiver war (Gruppe 2), verbessern konnte. Demnach kann die Hypothese, dass körperliche Aktivität einen signifikanten Zusammenhang mit nachfolgender Stimmung in ADHS PatientInnen aufweist, bezogen auf positiven Affekt, bestätigt werden. Für negativen Affekt kann die Hypothese lediglich für diejenigen ADHS PatientInnen bestätigt werden, die hyperaktiver sind.

Abschließend werden im letzten Kapitel Erfahrungen und Limitationen der in dieser Arbeit aufgeführten, sowie vorheriger Ambulanten Assessment Studien zusammengefasst und daraus Implikationen für zukünftige Studien abgeleitet. Vorherige Ambulante Assessment Studien im Bereich ‚körperliche Aktivität und Stimmung' zeigten generell Limitationen bezüglich fehlender Kontrollgruppen, Selbstreports statt objektiven Messungen von körperlicher Aktivität und geringer statistischer Power. Des Weiteren gingen Studien häufig nicht auf die Sportart, das Intensitätslevel, Erfolg und Misserfolg, d.h. ein Spiel zu gewinnen oder zu verlieren, oder die Spezifikation der Stimmungsparameter ein. Die allgemeine Diskussion gibt weiterhin einen Überblick über mobile-(m)Health Komponenten, die in den verschiedenen klinischen Studien verwendet wurden und richtet den Fokus vor allem auf deren technischen und methodischen Innovationen. Auf dieser Grundlage werden Implikationen für technische und methodische Anforderungen beschrieben, die in zukünftigen Ambulanten Assessment Studien berücksichtigt werden sollten. Noch dazu beschreibt dieses Kapitel welche Komponenten und Funktionen im Ambulanten Assessment bereits jetzt helfen könnten die klinische Praxis zu unterstützen, indem sie durch die sogenannte ‚digitale Phänotypisierung' Diagnosen untermauern. Hier sind beispielsweise kognitive Tasks am Smartphone zu nennen, die als objektives Maß Impulsivität (z.B. mit dem „stop-signal-task") oder das Arbeitsgedächtnis (z.B. mit dem „spatial n-back or memory-updating task") testen. Außerdem wird diskutiert, wie Bewegungsmuster in der Akzelerometrie als digitale Marker zur Erkennung von Symptomatik in psychischen Erkrankungen eingesetzt werden könnten. Hier wären beispielsweise kurze Spektren in Bewegungsmustern zu nennen, die sich signifikant zwischen hyperaktiven ADHS PatientInnen und gesunden Kontrollen unterscheiden. Würde ein solcher digitaler Marker, beispielsweise für Hyperaktivität, gefunden werden, könnte er die Diagnostik in psychischen Erkrankungen und somit die klinische Praxis zusätzlich unterstützen.

Preface

Chapter II: Koch, E. D.; Tost, H.; Braun, U.; Gan, G.; Giurgiu, M.; Reinhard, I.; Zipf, A.; Meyer-Lindenberg, A.; Ebner-Priemer, U. W.; Reichert, M. (2018). Mood Dimensions Show Distinct Within-Subject Associations with Non-exercise Activity in Adolescents: An Ambulatory Assessment Study. *Frontiers in psychology*, *9*, 268. doi:10.3389/fpsyg.2018.00268

Chapter III: Koch, E. D.; Tost, H.; Braun, U.; Gan, G.; Giurgiu, M.; Reinhard, I.; Zipf, A.; Meyer-Lindenberg, A.; Ebner-Priemer, U. W.; Reichert, M. (2020). Relationships between incidental physical activity, exercise, and sports with subsequent mood in adolescents. *Scandinavian journal of medicine & science in sports*, *30*(11), 2234–2250. doi:10.1111/sms.13774

Chapter IV: Koch, E. D., Moukhtarian, T. R., Skirrow, C., Bozhilova, N., Asherson, P., & Ebner-Priemer, U. W. (2021). Using e-diaries to investigate ADHD - State-of-the-art and the promising feature of just-in-time-adaptive interventions. *Neuroscience and biobehavioral reviews, 127*, 884–898. doi:10.1016/j.neubiorev.2021.06.002

Chapter V: Koch, E. D., Freitag, C. M., Mayer, J. S., Medda, J., Reif, A., Grimm, O., Ramos-Quiroga, J. A., Sanchez, J. P., Asherson, P., Kuntsi, J., Pawley, A. D., Buitelaar, J. K., Bergsma, D., Ortega, F. B., Muntaner-Mas, A., Reinhard, I., Reichert, M., Giurgiu, M., & Ebner-Priemer, U. W. (2022). The dynamical association between physical activity and affect in the daily life of individuals with ADHD [Submitted version]. *European Neuropsychopharmacology*, *57*, 69–74. https://doi.org/10.1016/j.euroneuro.2022.01.110

General introduction

Physical activity is known to preserve human somatic and mental health (Pedersen & Saltin, 2015). However, globally, 28 percent of adults (Guthold et al., 2018) and 81 percent of adolescents (Guthold et al., 2020) are not sufficiently physically active. This is surprising since physical inactivity is known to be the fourth greatest risk factor for mortality worldwide (WHO, 2010). The positive effects of physical activity are reflected in a decrease of mortality and a decrease in rates of heart disease, cancer, diabetes mellitus, obesity, etc. (Pedersen & Saltin, 2015). Physical activity has positive effects on mental health, too, as is shown in improvements in mood, well-being, depression, anxiety, self-esteem, and the buffering of stress (Fuchs, 2003, 2012; Pedersen & Saltin, 2015).

Being in a bad mood or having a negative affect are co-occurring factors in mental disorders (Mikolajewski et al., 2013). Herein, the terms of mood, affect, and emotions are used interchangeably (Ekkekakis, 2013). However, in the scientific community, controversial discussions still exist about these constructs (Ekkekakis et al., 2001). To differentiate between terms, Ekkekakis (2012) defines core affect as a simple, nonreflective feeling based on broad dimensions, with general content and varying intensity over time. Affect can occur in an isolated form, or it can be a component of moods and emotions. According to Ekkekakis (2012), emotions are initiated by current events or caused by something specific. They are temporary and of a short duration. In contrast, mood is not necessarily associated with a current event, a cause, or something specific, and it lasts longer than emotions (Ekkekakis, 2012). Moreover, in addition to disagreements about the definitions of mood, there exist country- and author-dependent preferences for measuring mood and affective states. Specifically, researchers from the United States prefer a two-dimensional model, whereas researchers from Europe prefer a three-dimensional model. The two-dimensional model differentiates between positive and negative affect, which can be assessed using the Positive and Negative Affect Schedule (PANAS; Watson & Tellegen, 1985). Treating mood as a two-dimensional construct, the PANAS is a 20-item mood scale (i.e., ten positive and ten negative items) with good psychometric properties (Watson et al., 1988). Since the idea behind the Ambulatory Assessment method is to assess participants by using short questionnaires that can be completed on smartphones in the course of their daily lives, the authors shortened the PANAS, thus minimizing the burden on the study participants (Myin-Germeys et al., 2003; Wichers et al., 2010; Wigman et al., 2013). The three-dimensional model takes valence, energetic arousal, and tense arousal/calmness into account, which can be assessed using the Multidimensional Mood State Questionnaire (MDMQ; Steyer et al., 1997). Wilhelm and Schoebi (2007) demonstrated that the two-dimensional model fit their data when viewed from a between-subjective perspective (usually level two in a multilevel model), whereas the three-dimensional model was superior when viewed from a within-subject perspective (usually level one in a multilevel model). They revealed good psychometric properties for their three-dimensional short scale on the within-subject level (reliability coefficients: 0.70 for valence and calmness; 0.77 for energetic arousal). As more than two-thirds of the total latent variation was the result of fluctuations over time (Wilhelm & Schoebi, 2007), this three-dimensional mood questionnaire proved to be highly sensitive to capturing changes in mood, which is of central importance for within-subject analyses. For children, Leonhardt et al. (2016) modified the instrument from Wilhelm and Schoebi (2007). This instrument is currently one of the best validated instruments for assessing mood in children and adolescents through the use of electronic diaries (e-diaries) in real life; it is especially good at assessing within-subject dynamics (Leonhardt et al., 2016). Due to different research consortia and preferences in the trials, the four papers of the present work include both models and questionnaires.

Due to technical limitations in the past, capturing rapid fluctuations of affect (i.e., affective instability and lability) in individuals with mental disorders (e.g., mood disorders) was challenging. With innovative technical progress, it is currently feasible to monitor rapidly changing fluctuations in feelings and behavior using the Ambulatory Assessment method (Trull & Ebner-Priemer, 2013). From a technological point of view, Ambulatory Assessment is a state-of-the-art method to obtain deeper insight into the behavior and feelings of individuals in their everyday lives in the real world (Trull & Ebner-Priemer, 2013). With accelerometers and e-diaries, it is feasible to measure physical activity objectively and to ask subjects to report feeling states (e.g., affective states) several times a day (Ebner-Priemer et al., 2012). Furthermore, the Ambulatory Assessment method has many advantages, i.e., bypassing laboratory distortions and minimizing recall biases that might appear in paper-pencil questionnaires (Bussmann et al., 2009; Fahrenberg et al., 2007; Stone et al., 2002). Moreover, the Ambulatory Assessment method assesses both between-subject and within-subject effects (Kanning et al., 2015; Trull & Ebner-Priemer, 2013). Especially in patient groups with attention deficits, repeated real-time sampling may help subjects remain focused on filling out very short questionnaires several times a day rather than requiring them to complete an extensive end-of-the-day questionnaire that is afflicted by well-known recall biases (Bussmann et al., 2009). Thus, the Ambulatory Assessment method is currently recommended as the most promising method for investigating both affective states and physical activity in real time and real life (Kanning et al., 2013).

Physical activity is an umbrella term with several categories that needs to be defined. In the present work, we differentiate between nonexercise activity/incidental activity, exercise, and sports. Therefore, due to reviewer preferences, the terms nonexercise activity and incidental physical activity are used synonymously to describe daily life activities with an intended purpose such as cleaning, gardening, walking the dog, or running to catch a train (Kanning et al., 2013). Incidental physical activity may be an activity that is performed very spontaneously and with less energy expenditure than exercise and sports. In contrast, exercise and sports are planned activities and may require higher energy expenditures than incidental physical activity (Pink, 2008). In general, exercise and sports are related to a motive (i.e., improving fitness, strength, health, aesthetics, enjoyment of the exercise or the competition per se). Exercise as such can be defined as structured, planned, and repetitive movement for improving physical fitness with health as its main goal (Pink, 2008). In contrast, sport contains the idea of competition and most often entails higher levels of physical exertion, complex physical skills, internal or external rewards, official rules, and institutional characteristics (Pink, 2008).

The measurement of physical activity can be achieved by many methods, depending on research interests and research questions. Among others, common methods include the doubly labeled water method, cardiorespiratory fitness trackers, biomarkers, heart rate monitors, pedometers, and accelerometers (Prince et al., 2008). Accelerometry is the recording of the intensity and duration of raw movement acceleration signals (i.e., single- or multiaxial accelerations) measured across a corresponding period of time (Kavanagh & Menz, 2008; Reichert et al., 2020). The accelerometers used in the studies reported in the following papers are triaxial sensors that measure acceleration with a sampling frequency of 64 Hz and a range of ±8 g (for more technical details see movisens GmbH, 2021) worn either on a participant's hip (Koch et al., 2018, 2020) or on the wrist of the nondominant hand (Koch et al., 2022). The raw signal was high-pass filtered (0.25 Hz) to exclude gravitational components and low-pass filtered (11 Hz) to eliminate artifacts that are not part of human movements (van Someren et al., 1996). The signal was then converted into model-specific outcome metrics that can be further processed and combined with e-diaries (e.g., Giurgiu et al., 2019; Reichert et al., 2016). In addition, objectively measured physical activity showed higher validity than subjective self-ratings of physical activity in daily life (Adamo et al., 2009; Prince et al., 2008).

Hence, the main goals of the four papers included in this work are the investigation of associations between physical activity and mood within a community-based adolescent sample and within a clinical sample with individuals with attention-deficit/hyperactivity disorder (ADHD). The participants were monitored using the abovementioned mobile health (mHealth) devices (i.e., smartphones and accelerometers) and the partly modified instruments described in Leonhardt et al. (2016); Myin-Germeys et al. (2003); Wichers et al. (2010); and Wigman et al. (2013). The research questions and main findings are briefly introduced in the following.

Topic 1: Is mood related to subsequent incidental physical activity in adolescents?

Preliminary evidence suggests that mood (as a predictor) drives physical activity (as an outcome) within individuals (Liao et al., 2015). However, recent studies still showed methodological limitations (for an overview see Liao et al., 2015). Reichert et al. (2016) overcame some of these limitations and could confirm the finding that mood is an antecedent for spontaneous incidental physical activity (e.g., catching the train) within adults' everyday lives. To examine this association in a community-based adolescent sample, we investigated in the first paper of this work the effect of mood as a three-dimensional construct (i.e., valence, energetic arousal, and calmness) on incidental physical activity (Koch et al., 2018). Our results suggest that in adolescents, valence and energetic arousal are positively related, and calmness is negatively related, to subsequent incidental physical activity. Hence, mood is related to subsequent incidental physical activity in healthy adolescents (Koch et al., 2018).

Topic 2: Are incidental physical activity, exercise, and sports related to subsequent mood in adolescents?

In investigations on whether mood is also a consequence of physical activity, the findings are inconsistent (Bossmann et al., 2013; Gauvin et al., 1996; Kanning, 2012; Kanning et al., 2013, 2015; Schwerdtfeger et al., 2008). Some investigations found an association, and others did not, or they found an association only in one of the three mood dimensions (i.e., valence, energetic arousal, or calmness). However, in focusing on physical activity (as a predictor) and mood (as an outcome), studies have reflected differences in how the term physical activity is defined. This is shown in Reichert et al. (2017), whose results suggest that incidental physical activity (e.g., walking the dog) and exercise (e.g., running) have different effects on mood dimensions in adults. Specifically, incidental physical activity increased energetic arousal but decreased calmness, whereas exercise increased valence and calmness in adults, thus unravelling some of the prior confusing findings. We also investigated this association in a community-based adolescent sample by separating physical activity into incidental physical activity, exercise, and sports, as explained above (Koch et al., 2020). We found that healthy adolescents feel better and more energized after incidental physical activity (e.g., walking the dog); they feel better but less calm after exercise (e.g., skating); and they feel less energized after sports (e.g., playing soccer). Hence, incidental physical activity, exercise, and sports are related to subsequent mood in healthy adolescents in consideration of the mood dimensions (Koch et al., 2020).

Topic 3: State-of-the-art of Ambulatory Assessment studies in ADHD.

In comparison to the feelings and behaviors of healthy individuals, the feelings and behaviors of individuals with mental disorders fluctuate rapidly in the course of daily life (Aase & Sagvolden, 2005; Ebner-Priemer et al., 2009; Jones et al., 2018; Pedersen et al., 2019; Trull et al., 2015). Hence, it is even more important to use an appropriate method to capture these fluctuations adequately (Ebner-Priemer et al., 2009; Ebner-Priemer & Trull, 2014). In our third paper, we provide an overview of e-diary studies investigating individuals with ADHD. In short, Ambulatory Assessment has been shown to be a helpful method to understand dynamic patterns in ADHD that cannot be studied in physicians' offices, laboratories, or clinical settings. Ambulatory Assessment can support psychiatric practices to improve diagnoses by revealing fluctuations over time that could be relevant in a clinical context (Brietzke et al., 2019). More specifically, we concluded that the understanding of underlying mechanisms and related components of a disorder paves the way to more effectively alleviating conditions. The similarity of symptoms, co-occurring symptoms, comorbidities, and side effects, especially in mood disorders (e.g., major depressive disorder), makes the diagnosis of a disorder challenging at times. By combining diagnostic methods, it is possible to overcome methodological weaknesses or false diagnoses. With technical progress, digital phenotyping has become feasible, simplifying the diagnosis of patients by closely monitoring the respective physical parameters of their symptoms, feelings, and behaviors in their daily lives, which was not possible in the past. In addition, future directions for research using technology that already exists but that is still in its infancy are presented. Future technological progress will facilitate the identification of phenotypes using digital tools to help establish interventions and therapies, thus addressing the specific needs of patients even more individually and effectively (Koch et al., 2021).

To date, state-of-the-art Ambulatory Assessment studies in ADHD research still are in their infancy. Studies show that patients with ADHD experience elevated variability and intensity of negative affect, which is related to emotional variability, frustration, sadness, anger, anxiety, stress, functional impairment, peer victimization, alcohol drinking, and smoking (Koch et al., 2021). However, existing studies primarily used self-report and cardiovascular monitoring (for an overview see Koch et al., 2021) and did not exploit the full range of data collection modalities. Hence, future studies should increasingly use and combine the innovative features of the Ambulatory Assessment method to better understand the associations of the disorder.

Topic 4: Is physical activity related to subsequent positive and negative affect in individuals with ADHD?

Ambulatory Assessment studies have shown that physical activity is positively associated with affective states and well-being in both healthy individuals (Koch et al., 2018, 2020; Reichert et al., 2016; Reichert et al., 2017) and individuals with mental disorders (i.e., depressive, anxiety, bipolar, borderline personality disorder, and schizophrenia; Kanning et al., 2013). ADHD is a neuropsychiatric disorder characterized by symptoms such as inattention, hyperactivity, and impulsivity that lead to functional impairment (Biederman, 2005). Between three and five percent of school-age children suffer from ADHD (Polanczyk et al., 2014), and approximately fifty percent of these children carry the disorder into adulthood (Sobanski & Alm, 2004; Weiss & Hechtman, 1993). Further worsening the outcomes of the disorder, ADHD is associated with many comorbidities and co-occurring symptoms (e.g., affective instability, mood and anxiety disorders, depression, substance use disorders, and personality disorders) (Anastopoulos et al., 2011; Broome et al., 2015; Katzman et al., 2017). Up to 60% of children with ADHD show at least one additional comorbidity that is classified in the *Diagnostic and Statistical Manual of Mental Disorders* (Angold et al., 1999; August et al., 1996). There is evidence that, due to overlapping symptoms among mental disorders, the improvement of comorbidities and co-occurring symptoms may also have a positive effect on the main ADHD symptoms (Patel et al., 2012).

One co-occurring symptom that has a positive relationship to ADHD symptoms (i.e., impulsivity and hyperactivity) in adolescents is negative affect (Loney et al., 2006). Okado et al. (2016) showed that adolescents with ADHD with comorbidities (i.e., mainly an internalizing disorder) have higher levels of negative affect. Although associations between physical and mental parameters in mental disorders have been shown to be dynamic in nature (Trull et al., 2008; Trull et al., 2015), studies investigating these fluctuating processes in individuals with ADHD using the Ambulatory Assessment method are rare. Hence, we investigated the dynamic processes of physical activity and positive and negative affect in individuals with ADHD using accelerometers and e-diaries (Koch et al., 2022). Our findings suggest that positive affect is improved by increased physical activity in individuals with ADHD (i.e., Group 1 individuals with ADHD who are predominantly inattentive and Group 2 individuals with ADHD showing the combined presentation of symptoms) and in healthy controls. Furthermore, with increased levels of physical activity, negative affect could be improved among those patients who were more hyperactive than others (i.e., Group 2: individuals with ADHD showing the combined presentation of symptoms). However, we could not find an effect of physical activity on negative affect in the patient sample that was predominantly inattentive (i.e., Group 1 individuals, who were less hyperactive than the others) and in healthy controls. Hence, physical activity is related to subsequent positive affect in individuals with ADHD. However, depending on the specific characteristics of the main ADHD symptoms, physical activity is related to subsequent negative affect only in the patient group that is more hyperactive than the others (Koch et al., 2022).

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Paper I

Mood Dimensions show Distinct Within-Subject Associations with Non-exercise Activity in Adolescents: An Ambulatory Assessment Study

Slightly modified version of the published paper

Koch, E. D.; Tost, H.; Braun, U.; Gan, G.; Giurgiu, M.; Reinhard, I.; Zipf, A.; Meyer-Lindenberg, A.; Ebner-Priemer, U. W.; Reichert, M. (2018). Mood Dimensions Show Distinct Within-Subject Associations with Non-exercise Activity in Adolescents: An Ambulatory Assessment Study.

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Abstract: Physical activity is known to preserve both physical and mental health. However, the physical activity levels of a large proportion of adolescents are insufficient. This is critical, since physical activity levels in youth have been shown to translate into adulthood. Whereas in adult populations, mood has been supposed to be one important psychological factor that drives physical activity in everyday life, this issue has been poorly studied in adolescent populations. Ambulatory Assessment is the state-of-the-art approach to investigate how mood and non-exercise activity fluctuate within persons in everyday life. Through assessments in real time and real life, this method provides ecological validity, bypassing several limitations of traditional assessment methods (e.g., recall biases). To investigate whether mood is associated with non-exercise activity in adolescents, we equipped a community-based sample comprising 113 participants, aged 12–17 years, with GPS-triggered e-diaries querying for valence, energetic arousal, and calmness, and with accelerometers continuously measuring physical activity in their everyday lives for 1 week. We excluded all acceleration data due to participants' exercise activities and thereafter we parameterized non-exercise activity as the mean value across 10-min intervals of movement acceleration intensity following each e-diary prompt. We used multilevel analyses to compute the effects of the mood dimensions on non-exercise activity within 10-min intervals directly following each e-diary prompt. Additionally, we conducted explorative analyses of the time course of the effects, i.e., on different timeframes of non-exercise activity up to 300 min following the mood assessment. The results showed that valence ($p < 0.001$) and energetic arousal ($p < 0.001$) were positively associated with non-exercise activity within the 10 min interval, whereas calmness ($p < 0.001$) was negatively associated with non-exercise activity. Specifically, adolescents who felt more content, full of energy, or less calm were more physically active in subsequent timeframes. Overall, our results demonstrate significant associations of mood with non-exercise activity in younger ages and converge with the previously observed association between mood and physical activity in

adults. This knowledge on distinct associations of mood-dimensions with non-exercise activity may help to foster physical activity levels in adolescents.

Introduction

In most European countries, less than half of adolescents meet the World Health Organization's physical activity recommendations (van Hecke et al., 2016; WHO, 2011). This is critical since low levels of physical activity during developmental stages have been shown to result in insufficient physical activity in adulthood (Telama et al., 2005) and to constitute a central risk factor for both severe somatic and psychiatric diseases (Pedersen & Saltin, 2015). Consequently, the promotion of physical activity in adolescents is a major health issue, e.g., for the prevention of metabolic syndrome and depression (Ahn & Fedewa, 2011; Janssen & Leblanc, 2010). In addition to structured exercise activities (e.g., jogging or playing soccer), an active lifestyle (e.g., walking to school instead of taking the school bus) has been shown to be related to health benefits (Healy et al., 2008; Wen et al., 2011).

To promote a healthy lifestyle, e.g., enhancing non-exercise activity levels in everyday life, an understanding of the psychological determinants of non-exercise activity is necessary. Recent studies have shown associations between mood and physical activity in everyday life, i.e., it has been supposed that mood influences physical activity (Liao et al., 2015; Liao et al., 2016a, 2016b; Schneider et al., 2009), and physical activity has been supposed to influence mood (Ebner-Priemer et al., 2013; Kanning et al., 2015; Kanning & Schlicht, 2010; Reichert et al., 2016; Schwerdtfeger et al., 2010) thus the causality of these effects remains still unknown (Kanning et al., 2013; Schwerdtfeger et al., 2010).

There are several theories supposing possible mechanisms that might explain the associations between mood and physical activity (Carels et al., 2007; Mata et al., 2012; Salovey et al., 2000; Seligman et al., 2005; Stathopoulou et al., 2006; Taquet et al., 2016; Thayer et al., 1994). For example, it is conceivable that people engage in physical activities to increase their low levels of mood (Mata et al., 2012; Stathopoulou et al., 2006; Taquet et al., 2016). This regulation theory (Thayer et al., 1994) suggests that low mood states precede physical activity bouts and make people move. Concurrently, one can hypothesize that people engage in physical activities to facilitate their high mood levels (Carels et al., 2007). This maintenance theory (Seligman et al., 2005; Salovey et al., 2000) suggests that high mood states precede physical activity bouts and make people move.

Technologically speaking, ambulatory assessment makes it feasible to study psychological processes in everyday life. Particularly, assessing mood via e-diaries on smartphones both in real time and in real life and capturing physical activity objectively with accelerometers enables the investigation of how mood and physical activity fluctuate within persons over time (Kanning et al., 2015; Ortega et al., 2013). This real time and real-life assessment technique, known as ambulatory assessment or ecological momentary assessment, comes with several advantages such as bypassing laboratory distortions and minimizing well-known recall biases of traditional approaches such as paper-pencil questionnaires (Bussmann et al., 2009; Fahrenberg et al., 2007; Stone, 2002). Additionally, objective physical activity measurements have shown increased validity compared to subjective self-ratings (Adamo et al., 2009; Prince et al., 2008). Most importantly, ambulatory assessment is a state-of-the-art technique that is used to investigate within-subject processes (Kanning et al., 2015; Trull & Ebner-Priemer, 2013). This is of special importance since conclusions from between-subject studies cannot be translated into within-subject processes. For example, at the between-subject level, people who are more physically active on average are the ones with habitually lower mean values of blood pressure, whereas physical activity increases acute blood-pressure at the within-subject level (e.g., bouts of physical activity in everyday life, such as running to the train station increasing a person's blood pressure; Kanning et al., 2013; Reichert et al., 2016).

In adolescents, there are currently few studies investigating the association of mood and physical activity. Specifically, Schneider et al. (2009) studied the association between affective responses to exercising and physical activity behaviors in the everyday lives of 124 adolescents aged 14-16 years. The participants were asked to perform two ramp-type cycle ergometer exercise tasks. Valence was assessed with an 11-point bipolar feeling scale before, during and after the exercise tasks. Thereafter, the participants wore an Actigraph® accelerometer on their left hips measuring the physical activity levels in their everyday lives. The affective response to the moderate-intensity exercise task was positively associated with physical activity levels in everyday life. However, the affective response to the high-intensity exercise task was not associated with the physical activity in everyday life. These findings led to the assumption that adolescents who show positive affective responses to moderate exercise are more likely to meet activity recommendations in their everyday lives than adolescents who feel uncomfortable with moderate exercise are. Dunton et al. (2014) analyzed the association between mood states and moderate to vigorous physical activity in the everyday lives of 119 children aged 9-13 years. The participants were asked to fill in e-diaries on smartphones for eight consecutive days and to wear accelerometers in their everyday lives. The analyses revealed increased levels of feeling energetic and decreased levels of fatigue before and after 30-minute bouts of moderate-to-vigorous physical activity compared to the children's affective baseline levels. Additionally, Dunton and colleagues (2014) revealed decreased levels of negative affect after 30-minute bouts of moderate-to-vigorous physical activity. Moreover, children who exercised more often showed a high stability of positive and negative affect during the entire study period. However, the analyses did not show any relation between positive affect and physical activity. Applying a laboratory approach, Subramaniapillai et al. (2016) investigated feelings of tranquility, revitalization, and physical exhaustion prior to and after a 20-minute exercise bout on a cycling ergometer in adolescent bipolar patients (n = 32) and healthy controls (n = 31), both aged 13-20 years. They found a small reduction in feelings of tranquility after exercise in both groups. Langguth et al. (2016) investigated the within-subject association between moderate-to-vigorous physical activity (MVPA) and depressed affect in the everyday lives of 72 adolescents aged 13-22 years. The participants wore accelerometers and filled in either online- or paper-pencil-based diaries reporting depressed affect at the beginning and the end of each of the eight consecutive days. Langguth et al. (2016) reported a significant positive association between the mean MVPA level across one day and the reported depressed affect the following morning on weekdays in young women. In practice, a 60-minute increase in MVPA significantly predicted a 50 percent decrease in next-morning depressed affect. However, this finding was limited to the data provided by women. Moreover, neither women nor men showed any relation between physical activity and affect on weekend days, and physical activity was not related to depressed affect in the evening either. Hulley et al. (2008) investigated the school tendencies of 5-10-year old children and found significantly increased arousal and affective valences in children traveling further distances. They assessed mood by using the children’s feeling scale and the children’s felt arousal scale and physical activity by a pedometer over a 2-week period in 99 children. Kühnhausen et al. (2013) investigated participants aged 8-11 years (N = 82) by applying the ambulatory assessment, i.e., attaching accelerometers and providing e-diaries for several weeks, but did not find any relation between physical activity and affect in everyday life.

In adults, the majority of ambulatory assessment studies on within-subject associations between mood and physical activity have shown significant positive relations between the mood dimension, energetic arousal, and physical activity (Dunton et al., 2014; Langguth et al., 2016; Reichert et al., 2016). Furthermore, a significant negative relation between calmness and physical activity was found (for an overview, refer to Liao et al., 2016). Findings on the within-subject associations between affective valence and physical activity remain ambiguous (Liao et al, 2016). Recently, Reichert and colleagues (2016) showed that there may be differential effects of physical activity on mood demonstrating that non-exercise activities (such as climbing stairs) significantly increased energetic arousal and decreased calmness, whereas exercise (such as jogging) significantly increased affective valence and calmness.

While the ambulatory assessment is a state-of-the-art approach for investigating within-subject associations between mood and non-exercise activity (Kanning, 2013), the few existing studies that have utilized this technique in adolescents have shown considerable limitations (Kühnhausen et al., 2013). First, though there are a couple of studies that have focused only on clinical samples (Gawrilow et al., 2016; Subramaniapillai et al., 2016), there have been few studies of healthy participants. Second, most of the existing studies have applied laboratory intervention designs that were concentrated on between-subject effects and, thus, did not reveal findings on the within-subject processes of the everyday lives of children and adolescents. Third, the majority of these studies used self-report assessments that are known to be less reliable than objective physical activity measurements are (Prince et al., 2008). Fourth, recent ambulatory assessment studies in adolescents revealed a lack of power regarding both sample size (between-subject level) and the amount of e-diary ratings (within-subject level). Fifth, parameterization of non-exercise activity is controversial. It is discussed whether it is more feasible to use categories (e.g., light physical activity, moderate to vigorous physical activity, etc.) or to apply a dimensional measurement, such as movement acceleration intensity (Dunton et al., 2014; Ebner-Priemer et al., 2013). Sixth, investigations of the associations between mood and physical activity across different time frames are lacking (Kühnhausen et al., 2013).

Thus, we investigated the association between mood and non-exercise activity in healthy participants to analyze within-subject processes in the everyday lives of adolescents. Furthermore, we conducted an ambulatory assessment study using e-diaries and accelerometers across seven days to study a large community-based sample of healthy adolescents. Non-exercise activity was measured via accelerometers and electronic diaries (e-diaries) on smartphones were applied to repeatedly assess mood (i.e., valence, energetic arousal and calmness) in real life and real time. Additionally, explorative analyses were conducted to investigate the time frames of physical activity that are associated with the three mood-dimensions of valence, energetic arousal and calmness.

Based on the findings of existing studies in adolescents and adults (Dunton et al., 2014; Hulley et al., 2008; Kühnhausen et al., 2013; Langguth et al., 2016; Reichert et al., 2016; Schneider et al., 2009; Subramaniapillai et al., 2016), we hypothesized a positive relationship between the mood dimension, energetic arousal, and subsequent non-exercise activity (hypothesis I). Furthermore, we expected a positive relationship between the mood dimension, valence, and subsequent non-exercise activity (hypothesis II) and a negative relationship between the mood dimension, calmness, and subsequent non-exercise activity (hypothesis III). Moreover, we conducted explorative analyses on the time scale of the effects.

Materials and Methods

Participants

Adolescents aged between 12-17 years were selected during a 29-month period (from April 2014 to January 2017) as part of the URGENCY study (Impact of Urbanicity on Genetics, Cerebral Functioning and Structure and Condition in Young People) at the psychiatric-epidemiological center (PEZ), Central Institute of Mental Health (CIMH), Mannheim, Germany. Participants received monetary compensation for their participation in the study. The exclusion criteria were acute diseases, current or previous cardiovascular disorders, mental disorders, and chronic endocrine or immunological diseases. Participants reported their exercise activities during the study following the same procedure that is described for adults in Reichert et al. (2016). This enabled a focus on the analyses of non-exercise activity through excluding e-diary prompts prior to or during exercise activities. Furthermore, the entire datasets of 6 out of 134 participants were excluded because of missing accelerometer data (devices got lost, recordings were incomplete, etc.); 12 out of 134 of the datasets were excluded for reasons including a large amount of accelerometer non-wear time; and 3 participants' datasets were excluded because of low e-diary compliance (<30%). Finally, the analyzed sample comprised N = 113 participants (48% female) with an average age of 15.02 years (SD = 1.70; see Table 1) and an average BMI of 20.14 kg/m^2 (SD = 2.66; see Table 1).

Table 1: Descriptive Characteristics

	N	Minimum	Maximum	Mean	SD
Age [years]	113	11.50	17.88	15.02	1.70
BMI [kg/m²]	113	14.10	29.40	20.14	2.66
Incidental activity [millig/participant/week]	113	13.32	74.78	40.86	11.87
Valence [mean/participant/week][a]	113	4.10	6.95	5.59	0.54
Calmness [mean/participant/week][a]	113	3.15	6.63	5.13	0.65
Energetic arousal [mean/participant/week][a]	113	3.27	6.22	4.55	0.63
Compliance [percent/week]	113	42.86	100.00	81.95	14.24
Compliance [prompts answered/per day]	113	5.14	13.43	6.37	0.97

[a]Mood (i.e., valence, energetic arousal, and calmness) was assessed on 7-point Likert scales (0–6); for details see method section.

Ambulatory Assessment Procedure

In the first step, participants were briefed on the usage of both the smartphone (Motorola Moto G) and the accelerometer (Move-II & Move-III) at the PEZ. Afterwards, participants were monitored for seven consecutive days in their everyday lives. A smartphone app (movisensXS, version 0.6.3658) was programmed to trigger e-diary prompts. The daily smartphone-based assessment period lasted from 16:00 to 20:30 on weekdays (Monday to Friday, to not interfere with school duties) and from 9:00 to 20:00 on weekends (Saturday, Sunday). Physical activity was measured continuously except during the night.

On weekdays, participants were asked to answer 4 to 7 prompts per day. On the weekend, participants were asked to complete 8 to 17 prompts per day. An acoustic signal, vibration and text on the smartphone invited participants to answer the mood questionnaire. Participants had the opportunity to delay a prompt for 5, 10 or 15 minutes in unfavorable situations. Since traditional time-based sampling might miss episodes of low and high levels of non-exercise activity (Ebner-Priemer et al., 2013), we used GPS-triggered e-diaries to capture episodes of low and high physical activity in everyday life. Specifically, the GPS trigger released a prompt when passing over a distance of 0.5 km. Additionally, two prompts per day occurred at fixed times (at 16:30 and 20:20). The minimum period between two consecutive prompts was 37 minutes and the maximum period was 77 minutes.

Because our analyses were focused on non-exercise activities, we excluded exercise times from our within-subject data. To this end, we asked participants to report on their exercise activities across the study week (i.e., exercise duration and time points) when returning the devices. We applied a well-tried procedure published in Reichert et al. (2017), which was similar to the Day Reconstruction Method (DRM; 15), used GPS-trajectories tracked via smartphone and involved displays on a digital map to enhance recall.

Measures

Non-exercise activity was assessed by a triaxial acceleration sensor (move-II or move-III), with a measurement range of ±8 g, a sampling frequency of 64 Hz, a resolution of 12 bits, and that was stored on an internal memory card. Participants wore the devices on their right hips across 7 days during wake hours. The assessment of mood was realized by using an instrument developed by Leonhardt and colleagues (2016). This instrument, based on the multidimensional mood questionnaire (Wilhelm & Schoebi, 2007), is, to the best of our knowledge, the only existing validated instrument for assessing mood in children and adolescents through e-diaries in real life. Leonhardt and colleagues (2016) showed this instrument to be appropriate for assessing within-subject dynamics of mood via e-diaries in everyday life. Accordingly, we assessed mood as a three-dimensional construct including good–bad mood, later referred to as valence (items: “cheerful, content, delighted, fantastic, good, afraid, mad, miserable, unhappy”), alertness–tiredness, later referred to as energetic arousal (items: “active, concentrated, interested, exhausted, faint, tired”), and calmness–tension, later referred to as calmness (items: “pleasant, rested, anxious, on edge, stressed”). We presented the items in a mixed order and with reversed polarity using seven-point Likert scales.

Analyses

First, the accelerometer data were processed, i.e., we computed the movement acceleration intensity [milli-g/min], with the DataAnalyzer (version 1.6.12129) software. Using a high-pass filter (0.25 Hz), gravitational components were excluded, and artifacts were eliminated by using a low-pass filter (11 Hz).

Second, the e-diary data and movement acceleration intensity [milli-g] data were combined using DataMerger (version 1.6.3868). We defined non-exercise activity as the aggregated mean movement acceleration intensity [milli-g] over 10-minute timeframes, as has been done in previous studies (e.g., Bossmann et al., 2013; Kanning, 2013; Kanning et al., 2013; Kanning et al., 2015; Reichert et al., 2016).

Third, statistical analyses were performed using SPSS (IBM; version 24). The mean movement acceleration intensity [milli-g] was aggregated for the 10-minute intervals after each answered e-diary assessment (later termed as [0–10]). Additionally, the time effects of mood on non-exercise activities were analyzed by aggregating the mean movement acceleration intensity [milli-g] in the 10-minute intervals following each answered e-diary assessment. Specifically, we aggregated the movement acceleration intensity [milli-g] in timeframes ranging from 11–20, 21–30 and up to 281–290 and 291–300 minutes (later termed as [11–20], [21–30], etc.). Moreover, we excluded e-diary-assessments that occurred within the 300 minutes prior to exercise activities (i.e., jogging, playing football, etc.). We log-transformed the outcome variables since the distribution of the non-exercise activity was right-skewed (caused by a high level of sedentary behavior) and showed only few high values (e.g., catching the train). Specifically, we log-transformed all values for the intervals ([0–10], [11–20], [21–30],…up to [291–300]) of the non-exercise activity using the natural logarithm.

Forth, we performed multilevel analyses to identify the within-subject effects of the mood dimensions (i.e., valence, energetic arousal and calmness) on non-exercise activity using the statistical software, SPSS (version 24, IBM). We nested repeated measurements (i.e., level 1) within participants (i.e., level 2) and calculated intra-class correlation coefficients. The logarithmized values of the non-exercise activity, i.e., the mean movement acceleration intensities in the 10-minute intervals after the mood assessments served as depended variable. The level 1 predictors time, time-squared, valence within-subject, energetic arousal within-subject, and calmness within-subject were included. The valence within-subject, energetic arousal within-subject, and calmness within-subject were person mean-centered around the mood scores within the study week. The predictors time and time-squared were transformed, i.e., we subtracted a value of 9 since adolescents received their e-diary prompts at the earliest time of 9:00. We controlled for any between-subject effects by adding the level

2 predictors of age, gender, BMI [kg/m2], and exercise/week [min]. Additionally, the mean mood scores were added as a level 2 predictor for each participant in terms of the between-subject values for valence, energetic arousal and calmness. Specifically, to calculate these predictors, we aggregated the mean mood scores for each participant over the whole study week. Random effects were added for every level 1 predictor. However, in the final model (Table 2), only the significant random effects were kept.

Table 2: Multilevel model analysis of the influences of the mood dimensions on non-exercise activity: fixed and random effects.

Outcome	Fixed				Random			
Predictor	**Beta**	**SE**	**df**	**p-value**	**Variance estimate**	**SD**	**Wald-Z**	**p-value**
Intercept	3.817	0.745	5.23	<0.001	1.353	0.034	39.673	<0.001
Time [hours]	0.351	0.027	13.14	<0.001				
Time-squared [hours^2]	-0.026	0.002	-	<0.001				
Age [years]	-0.0583	0.031	-	0.061				
Gender	-0.095	0.104	-	0.365				
BMI [kg/m^2]	-0.033	0.020	-	0.107				
Exercise/week [min]	0.001	0.000	2.105	0.039				
Valence within[a]	0.176	0.035	5.065	<0.001				
Energetic arousal within[a]	0.179	0.037	4.884	<0.001	0.056	0.017	3.226	0.001
Calmness within[a]	-0.164	0.030	-	<0.001				
Valence between[a]	0.263	0.133	1.975	0.053				
Energetic arousal between[a]	-0.014	0.098	-	0.885				
Calmness between[a]	-0.229	0.115	-	0.050				

[a]Mood (i.e., valence, energetic arousal, and calmness) was assessed on 7-point Likert scales (0–6); for details see method section.

Finally, we computed 30 multilevel models by varying the outcome variable (see Figure 2) to focus on either the short- or long-term impacts concerning mood and non-exercise activity. In detail, we incorporated the mean movement acceleration intensities (logarithmized values) aggregated across time frames [0–10], [11–20], [21–30],…up to [291–300]. However, only the level 2 predictors of age, valence between-subject, energetic arousal between-subject, and calmness between-subject were added. Random slopes were not considered for the analyses of time courses, only random intercepts. The α-level for all the analyses was set to 0.05.

Model 1: Main Model

Level 1 equation:

$Y_{ij} = \beta_{0j} + \beta_{1j} \times \text{Time of the day}_{ij} + \beta_{2j} \times \text{Time of the day}^2_{ij} + \beta_{3j} \times \text{Valence}_{ij} + \beta_{4j} \times$
$\text{Energetic Arousal}_{ij} + \beta_{5j} \times \text{Calmness}_{ij} + r_{ij}$

Level 2 equation:

$\beta_{0j} = \gamma_{00} + \gamma_{01} \times \text{Age}_j + \gamma_{02} \times \text{Gender}_j + \gamma_{03} \times \text{BMI}_j + \gamma_{04} \times \text{Exercise per week}_j + \gamma_{05} \times \text{Valence}_j +$
$\gamma_{06} \times \text{Energetic Arousal}_j + \gamma_{07} \times \text{Calmness}_j + u_{0j}$

$\beta_{1j} = \gamma_{10} + u_{1j}$

$\beta_{2j} = \gamma_{20}$

$\beta_{3j} = \gamma_{30}$

$\beta_{4j} = \gamma_{40} + u_{4j}$

$\beta_{5j} = \gamma_{50}$

Level 1 reflects the within-subject effects. The subscript *j* refers to participant *j* and the subscript *i* to the time of the e-diary entry. Thus, Y_{ij} represents the estimated level of non-exercise activity at a given time, *i*, in participant, *j*. The beta coefficients (β) at level 1 represent both the intercept and the effects of the time of the day, the time of the day squared, within-subject valence, energetic arousal, and calmness. r_{ij} represents the residuals. Level 2 reflects the between-subject effects. As mentioned above, we kept only the random effects showing significance in our final model. Only two predictors, i.e., time of the day and energetic arousal, showed significant random slopes. Therefore, u_{1j} and u_{4j} represent the variation in the participants' individual slope estimates for the predictors time of the day and energetic arousal within-subject around the respective overall mean slope estimates (refer to Table 2).

Model 2: Analyses of Time Course

We explored the short- and long-term effects of mood on non-exercise activity by calculating 30 multilevel models using different outcome variables, i.e., non-exercise activity within the time frames [0–10], [11–20], [21–30],…up to [291–300] min following each e-diary prompt. We applied the model specified above; however, we simplified the random part by only allowing for variation in the participants' individual intercepts (refer to model equation below).

Level 1 equation:

$$Y_{ij} = \beta_{0j} + \beta_{1j} \times \text{Time of the day}_{ij} + \beta_{2j} \times \text{Time of the day}^2_{ij} + \beta_{3j} \times \text{Valenceij} + \beta_{4j} \times \text{Energetic Arousal}_{ij} + \beta_{5j} \times \text{Calmness}_{ij} + r_{ij}$$

Level 2 equation:

$$\beta_{0j} = \gamma_{00} + \gamma_{01} \times \text{Age}_j + \gamma_{02} \times \text{Exercise per week}_j + \gamma_{03} \times \text{Valence}_j + \gamma_{04} \times \text{Energetic Arousal}_j + \gamma_{05} \times \text{Calmness}_j + u_{0j}$$

$$\beta_{1j} = \gamma_{10}$$

$$\beta_{2j} = \gamma_{20}$$

$$\beta_{3j} = \gamma_{30}$$

$$\beta_{4j} = \gamma_{40}$$

$$\beta_{5\,j} = \gamma_{50}$$

To make practical conclusions regarding the impacts of changes in mood dimensions on non-exercise activity, we computed percentage change rates using the equation below. A mood-increase of 1 point (mood was rated on Likert-scales from 1 to 7) will lead to a percentage change of non-exercise activity by

$$\delta = ((e^{\beta(\text{valence, energetic arousal, or calmness}) \times 1}) - 1) \times 100.$$

Ethical Considerations

The ethics committee of the Medical Faculty Mannheim at the Heidelberg University approved the study. The ethical guidelines for medical research (i.e., the Declaration of Helsinki) were followed. Information concerning the procedures in the study was communicated to all adolescent participants and their parents before written consent was obtained by their parents. The participants were free to withdraw from the study at any time.

Results

Descriptive Statistics

On average, the participants answered 45.12 (*SD* = 7.8) mood assessments/participant/week, corresponding to an overall e-diary compliance of 82% (*SD* = 14.23). The participants' mean valence was 5.59 (*SD* = 0.54), their mean energetic arousal was 4.55 (*SD* = 0.65), and their mean calmness was 5.12 (*SD* = 0.63, refer to Table 1). As described above, we defined non-exercise activity as the mean physical activity across the 10-min intervals directly following the e-diary prompts. On average, the participants' non-exercise activity across the whole study period was 40.86 mg/participant/min (range = 13.32–74.78; *SD* = 11.87). For reasons of comparison, it should be noted that according to Anastasopoulou et al. (2014), sedentary behavior (such as sitting) results in approximately 7 mg, walking (3.1 mph gait speed) in approximately 367 mg, and jogging (6.5 mph gait speed) in approximately 1,103 mg. Within-subject variations in non-exercise activity accounted for 69% of the total variance (intra-class correlation coefficient, ρ_I = 0.041). Sixty-eight participants (76%) engaged in exercise within the study week, on average, for 186.2 min/participant/week (*SD* = 137.8). Since we focused our analyses on non-exercise activity (such as climbing stairs or gardening), we excluded all e-diary prompts if exercise followed in the 300 min following the prompts (which was the case in 9% of all prompts), resulting in a final dataset of 3590 mood assessments.

Influence of Mood on Non-exercise Activity

Our results revealed significant within-subject associations for each of the three mood dimensions (i.e., valence, energetic arousal, and calmness) with non-exercise activity. Table 2 shows the influences of various within-subject (level 1) and between-subject (level 2) predictors on non-exercise activity, which we parameterized as the 10-min intervals of physical activity directly following each e-diary entry. In detail, energetic arousal showed the expected (hypothesis I) positive, within-subject association with non-exercise activity (beta coefficient = 0.179; $p < 0.001$; refer to Table 2). In practice, a 1 point increase (on a Likert scale from 1 to 7) in energetic arousal led to an average increase in non-exercise activity of around 20% across the 10 min following the e-diary assessment. The mood dimension, valence, was positively correlated with non-exercise activity, as well (beta coefficient = 0.177; $p < 0.001$; refer to Table 2), thus, confirming hypothesis II. In particular, when a participant's valence increased by 1 point (on a likert scale from 1 to 7), their non-exercise activity was increased, on average, by around 19% across the 10-min interval following the e-diary prompt. Calmness showed the expected (hypothesis III) significant association with non-exercise activity ($p < 0.001$; refer to Table 2); however, the effect was in the negative direction (beta coefficient = −0.164; refer to Table 2). In other words, when participants felt 1 point calmer (on a Likert scale from 1 to 7), their subsequent non-exercise activity in the 10 min after the e-diary prompt was decreased by approximately around 15%. In summary, all three mood dimensions showed comparable magnitudes of effects on non-exercise activity (beta coefficient of valence = 0.177, beta coefficient of energetic arousal = 0.179, beta coefficient of calmness = −0.164, refer to Table 2). Moreover, a significant random effect of the mood dimension, energetic arousal, revealed variability in the within-subject association of this mood dimension with non-exercise activity between subjects (beta coefficient = 0.056; $p = 0.001$; refer to Table 2).

Additionally, the within-subject predictors, time of day and time of day squared, revealed significant effects on non-exercise activity (beta coefficient of time = 0.351, $p < 0.001$; beta coefficient of time-squared = −0.026, $p < 0.001$). In practice, the effect of the time of day on non-exercise activity was reversely u-shaped, i.e., non-exercise activity increased from the daily study start time (at approximately 9:00) to the afternoon (approximately 16:00) and then decreased until the study end time (at approximately 20:00; see Figure 1). Moreover, the predictor calmness between-subject was significantly associated with non-exercise activity, and the predictor valence between-subject approached significance ($p = 0.050$ and $p = 0.053$, respectively; refer to Table 1). In practice, participants with a higher average valence over the study week showed a higher average amount of non-exercise activity within the 10-min intervals following the e-diary prompts (beta coefficient = 0.263; $p = 0.053$). Similarly, participants feeling, on average, calmer throughout the study week showed lower non-exercise activity levels (beta coefficient = −0.229; $p = 0.050$; refer to Table 2) on average. Furthermore, the amount of exercise (in min) in which adolescents engaged in throughout the study week was significantly related to the non-exercise activity following the e-diary entries. In practice, adolescents who engaged in more exercise within the study week were the ones who were more physically active in their everyday lives, as well. Neither age, body mass index (BMI) nor gender showed an association with non-exercise activity.

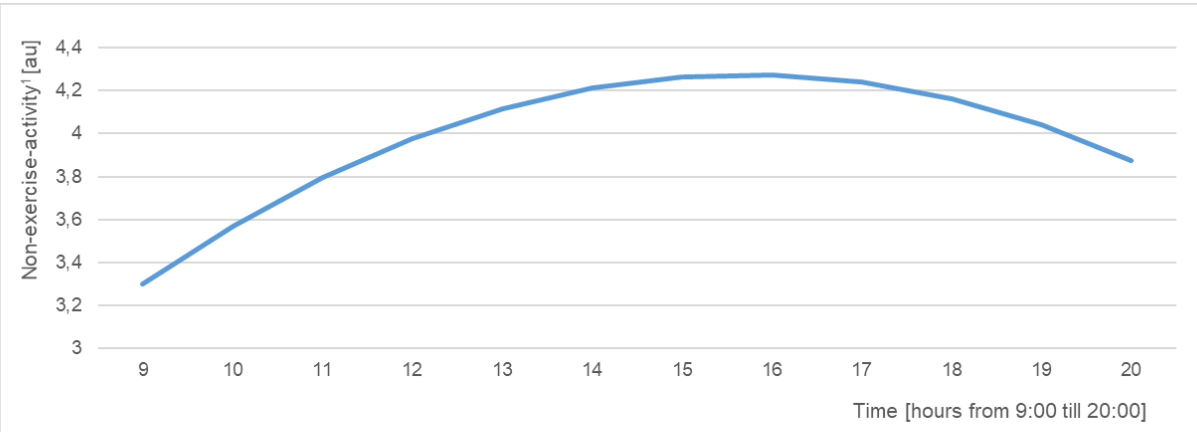

Figure 1: NEA in the course of the day. The daily time effect on non-exercise activity was reversely u-shaped. From the daily study start time (at approximately 9:00) non-exercise activity increased to the afternoon (at approximately 16:00) and decreased then until the study end time (at approximately 20:00). [1]Arbitrary unit: values are based on milli-g but log-transformed for statistical reasons (for details refer to the methods section).

Time Course of Within-Subject Associations Between Mood and Non-exercise Activity

Within-subject relations between mood and physical activity have mostly been investigated using relatively short periods of physical activity (Kanning and Schlicht, 2010; Kanning, 2013; Kanning et al., 2013, 2015; Dunton et al., 2014; Liao et al., 2017a,b). Only a few studies have investigated the time course of the effects between physical activity and mood (e.g., Schwerdtfeger et al., 2010; Reichert et al., 2016b, 2017). To the best of our knowledge, there has been no investigation of this issue in adolescents. To investigate the time course of within-subject associations between mood and non-exercise activity, we conducted multiple multilevel-analyses in which similar models to our full multilevel model presented above (refer to Table 2) were applied. We incorporated consecutive 10-min timeframes of non-exercise activity following the e-diary entries, i.e., non-exercise activity within 11–20, 21–30,…up to 281–290 and 291–300 min following the e-diary entries, later called [11–20], [21–30], etc.

On the y-axis of Figure 2, the beta coefficients of the multilevel models are depicted, i.e., each mood dimension (valence, energetic arousal, and calmness) predicting non-exercise activity aggregated across the consecutive 10-min intervals after the e-diary prompt (i.e., 1–10 min; 11–20 min, […], 291–300 min; refer to the x-axis).

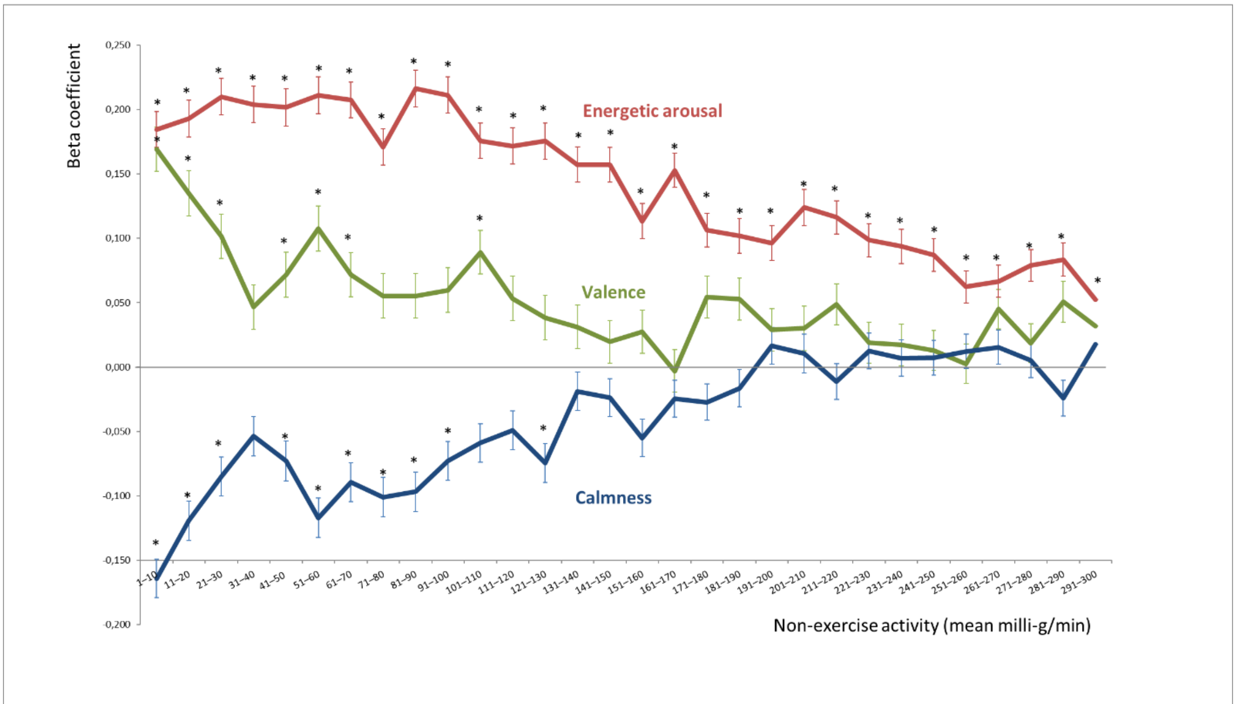

Figure 2: Effects of mood on non-exercise activity aggregated across subsequent 10-min intervals after the e-diary prompt. The beta coefficients for valence, energetic arousal, and calmness predicting non-exercise activity are presented at the y-axis. The x-axis shows the 10-min intervals of non-exercise activity, e.g., the mean non-exercise activity from min 31 up to min 40 after an e-diary prompt is represented by the axis label [31–40]. Significant effects of valence, energetic arousal and calmness predicting 10-min intervals of non-exercise activity are indicated with * ($p \leq 0.05$).

For all three mood dimensions, Figure 2 shows the diluting effects over time. In particular, the effects of calmness on non-exercise activity approached zero within the 300-min period after the e-diary prompts; the effects of valence and energetic arousal decreased toward zero, showing the robustness of our significant findings across time. In detail, valence showed significant associations with non-exercise activity only in the first hour after the e-diary prompt and in the timeframes [101–110] and [281–290] (refer to Figure 2). In contrast, the beta coefficients of energetic arousal predicting non-exercise activity showed significance across all timeframes suggesting a strong and stable effect. However, again, the association of energetic arousal with non-exercise activity decreased over time [from [1–10] (beta coefficient = 0.179; $p < 0.001$) to [291–300] (beta coefficient = 0.053; $p = 0.041$)]. This aligned with the findings from our main model, revealing a high influence of energetic arousal on non-exercise activity. Moreover, the mood dimension, calmness, showed a significant relation with non-exercise activity in time frames up to 130 min after the e-diary prompt, again supporting the findings from the main model showing that calmness exerted a negative influence on non-exercise activity. However, looking at the influences of calmness on non-exercise activity over time, some time frames up to 130 min after the e-diary prompt, i.e., [31–40] and [101–120] and the time points onwards, i.e., [131–300], did not reach significance.

Discussion

We investigated the effects of several mood dimensions (i.e., valence, energetic arousal, and calmness) on non-exercise activity in a community-based sample of healthy adolescents. As expected, our analyses showed significant within-person influences of all three mood dimensions on non-exercise activity.

First, we found a significant, positive within-subject correlation between the mood dimension, energetic arousal, and subsequent non-exercise activity, thus, confirming our hypothesis I. We found indicators of a robust effect of energetic arousal on non-exercise activity, i.e., both a high beta coefficient of energetic arousal predicting non-exercise activity in the 10-min interval following the mood assessment and significant associations between energetic arousal and non-exercise activity across all timeframes up to 300 min after the mood assessments. Indeed, our finding of a significant within-subject correlation between the mood dimension, energetic arousal, and subsequent non-exercise activity was in line with the results from Dunton et al. (2014), who showed that children aged 11–13 years engaged in more moderate to vigorous physical activity following higher ratings of feeling energetic and lower ratings of feeling tired. Although methodologically very different, Hulley et al.'s results (2008), revealing that children aged 5–11 years with greater distances between their home and school showed significantly increased felt-arousal-scores, supported our findings as well. Furthermore, our findings were in line with ambulatory assessment studies of adults that showed energetic arousal to be strongly related with non-exercise activity (Schwerdtfeger et al., 2010; Reichert et al., 2016b). As already mentioned above, studies in adolescents investigating the relation between mood and non-exercise activity in daily life do not exist.

Second, we found a positive association between valence and subsequent non-exercise activity at the within-subject level in adolescents, thus confirming our hypothesis II. However, valence appeared to be the mood dimension with the weakest association with non-exercise activity in adolescents. This was evidenced by comparing the beta coefficient to those of the other mood dimensions (i.e., energetic arousal and calmness) and by the time course of the effects across the different timeframes of non-exercise activity after the e-diary prompt. This finding was generally in line with previous studies in adults (for a discussion refer to Reichert et al., 2016b). Interestingly, in adolescents, we found valence to be significantly associated with non-exercise activity in timeframes up to 100 min. In contrast, in adults, Reichert et al. (2016b) found that only the 10-min timeframe after the mood assessment was significantly related with non-exercise activity. This might suppose that the association of valence and non-exercise activity is more pronounced in adolescence compared to adulthood. Further research is needed to substantiate this claim. Moreover, our model showed significant effects of valence on non-exercise activity at the between-subject level. In practice, persons with higher mean valence scores across the study week showed higher non-exercise activity levels, on average, across all 10-min timeframes after their mood assessments within the study week. This is not surprising since a couple of cross-sectional studies revealed that adolescents with higher physical activity levels showed higher levels of well-being (Donaldson and Ronan, 2006).

Third, calmness showed significant, negative within-subject associations with non-exercise activity. In particular, when adolescents felt calmer, they showed decreased levels of non-exercise activity both in the 10 min after the e-diary assessment and in timeframes up to 130 min. Since most of the existing studies have treated mood as a two-dimensional construct, not taking into account the dimension of calmness, there are only a few results on associations of this mood dimension with physical activity (Liao et al., 2015). Reichert et al. (2016b) showed increased calmness to be associated with decreased levels of non-exercise activity within adults, as well. In our model, the negative association between calmness and subsequent non-exercise activity held true for the between-subject level also, i.e., adolescents with higher mean calmness scores across the study week showed lower non-exercise activity levels across all 10-min timeframes after the mood assessment.

The results of our study provide evidence for both the maintenance theory (Salovey et al., 2000; Seligman et al., 2005) and the regulation theory (Thayer et al., 1994). In particular, we found that both increased energetic arousal and increased valence were associated with subsequently increased non-exercise activity supposing that positive mood states made people move thus supporting the maintenance theory (Salovey et al., 2000; Seligman et al., 2005). Apart from that, our data showed that decreased calmness was associated with subsequently increased non-exercise activity supposing that this negative mood state made people move. Therefore, our data does support the regulation theory (Thayer et al., 1994), too.

Limitations

First, a clear differentiation between non-exercise activity and exercise is important when investigating associations between physical activity and mood since both kinds of physical activity have shown distinct effects on mood (Reichert et al., 2017). We focused the analyses of our study on non-exercise activities (e.g., climbing stairs). Thus, excluding exercise activities (e.g., playing soccer) enabled us to make unambiguous statements on the associations between mood and non-exercise activity in adolescents. However, exercise in general and different exercise intensities in particular, that lead to both distinct behavioral responses (e.g., subjective perception of effort) and physiological responses (e.g., heart rate, lactate concentration), may be associated with distinct mood levels in adolescents. For example, studies in adults showed that physical activities with high intensity lead to decreases in mood (Ekkekakis et al., 2008; Schlicht et al., 2013). Thus, future studies should investigate within-subject associations between mood states and exercise at different intensities in adolescents. Second, our study included adolescents in different stages of biological development (puberty stages), i.e., participants aged 12–17 years. We cannot exclude the possibility that the effects of mood on non-exercise activity might differ among those puberty stages. However, to control for any age effects, we incorporated age as a dimensional predictor in our main model, and found that it showed non-significance. Additionally, we computed the interactions of the mood dimensions with age (as a dimensional variable) predicting non-exercise activity in an explorative manner but found no significant interaction effects. Third, since we were interested in the impacts of mood on non-exercise activities, we parametrized non-exercise activity in 10-min intervals following each e-diary prompt. However, the chronology of our independent variables (i.e., mood-dimensions) and dependent variables (i.e., non-exercise activity) constituted only one aspect of causality (Susser, 1991). This, by no means, proved the causality of our results, e.g., since there may be hidden third variables showing similar timely characteristics to the investigated mood dimensions. Since there have been many studies showing the other direction of effects, i.e., physical activity in everyday life increasing mood (Schwerdtfeger et al., 2010; Dunton et al., 2014; Kanning et al., 2015; Reichert et al., 2017), one might suggest that the relation between physical activity and mood may be circular

(Schwerdtfeger et al., 2010). To substantiate this hypothesis, further studies are needed. One approach may be to use ecological momentary interventions, e.g., to specifically alter physical activity levels in everyday life and investigate changes in mood (Myin-Germeys et al., 2016). Fourth, our participants attended school on weekdays. Accordingly, their physical activity patterns were limited during school times (usually pupils are forced to remain seated during classes). Since this artificially limits the variance in non-exercise activity (and pupils were not allowed to use smartphones in school), we prompted the e-diaries on weekdays from 16:00 to 20:30. We explored differences between the associations of the mood dimensions with non-exercise activity, comparing weekdays (16:00 to 20:30) to weekend days (9:00 to 20:00) by applying multilevel interaction analyses. One of the three mood dimensions, i.e., energetic arousal, showed a significantly higher correlation with non-exercise activity on weekend days compared to weekdays. Accordingly, further research is needed, e.g., ambulatory assessments across whole weekdays within adolescents' holidays.

Conclusion

In our study, we investigated how mood and physical activity fluctuate within adolescents in everyday life over time. This understudied association may play an important role in understanding what drives physical activity levels in developmental stages of puberty and is of special importance particularly since physical activity in adolescence predicts physical activity in adulthood (Telama et al., 2005). Applying sophisticated ambulatory assessment procedures, i.e., repeated GPS-triggered mood assessments in real time and objective physical activity measurements in the everyday life of a community-based sample comprising 113 participants aged 12–17 years, we found both valence and energetic arousal to be positively related to subsequent non-exercise activity and calmness to be negatively related to subsequent non-exercise activity. In practice, when adolescents felt better and content, more awake and full of energy, or less calm and relaxed, they engaged more in non-exercise activity within the subsequent timeframe. These findings may help to understand the psychological correlates of physical activity in adolescents' everyday lives, thereby, possibly contributing to the facilitation of physical activity and its beneficial health-promoting effects on the developmental stages of puberty. However, further research is needed, e.g., to unravel the relevant neurobiological foundations and to develop useful practical interventions.

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Paper II

Relationships between Incidental Physical Activity, Exercise, and Sports with subsequent Mood in Adolescents

Slightly modified version of the published paper

Koch, E. D.; Tost, H.; Braun, U.; Gan, G.; Giurgiu, M.; Reinhard, I.; Zipf, A.; Meyer-Lindenberg, A.; Ebner-Priemer, U. W.; Reichert, M. (2020). Relationships between incidental physical activity, exercise, and sports with subsequent mood in adolescents.

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Abstract

Physical activity is beneficial for human physical health and well-being. Accordingly, the association between physical activity and mood in everyday life has been a subject of several Ambulatory Assessment studies. This mechanism has been studied in children, adults and the elderly, but neglected in adolescents. It is critical to examine this mechanism in adolescents because adolescence plays a key role in human development and adolescents' physical activity behavior translates into their behavior in adulthood.

We investigated adolescents' mood in relation to distinct physical activities: incidental activity such as climbing stairs; exercise activity, such as skating; and sports, such as playing soccer. We equipped 134 adolescents aged 12-17 years with accelerometers and GPS-triggered electronic diaries to use in their everyday life. Adolescents reported on mood repeatedly in real-time across seven days and this data was analyzed using multilevel-modeling.

After incidental activity, adolescents felt better and more energized. After exercise, adolescents felt better but less calm. After sports, adolescents felt less energized. Analyses of the time course of the effects confirmed our findings.

Physical activity influences mood in adolescents' everyday life, but has distinct effects depending on the kind of physical activity. Our results suggest incidental and exercise activities entails higher post-bout valence compared to sports in competitive settings. These findings may serve as an important empirical basis for the targeted application of distinct physical activities to foster well-being in adolescence.

Introduction

Physical activity can improve well-being (WHO, 2013) and fosters physical health (Janssen & Leblanc, 2010). Nevertheless, 81% of adolescents globally (aged 11–17 years) do not reach the level of physical activity necessary to sustain health that is recommended by the World Health Organization (WHO, 2013). Behavioral theories suggest positive feeling states (i.e., positive affective responses) after physical activity to drive individuals to repeat those activities (Mellers, 2000). As a long-term consequence, these positive feelings may lead to an active life style and thus improve well-being, promote health, and enhance quality of life (Mellers, 2000; Topp et al., 2015; WHO, 2013). Given that adolescents' physical activity behavior has been shown to translate into adulthood (Hallal et al., 2006), the investigation of the association between physical activity and mood in adolescents constitutes a major priority. According to the broad definition of Williams et al. (Williams et al., 2018), the umbrella term 'affect' describes an evaluative neurobiological state that includes core affect, emotion, and mood. Affect coordinates patterns of physiological and involuntary behavior changes (e.g., heart rate and facial expression) and subjective experiential feelings (e.g., pleasure, anger). Moods (e.g., feeling irritable, anxious, happy, or contented) share components with the construct of emotions but they are more diffuse, do not focus on a specific event or stimulus, and are less time-limited than emotions. For instance, anger may be an emotion that is related to a specific event and may pass quickly, but being in an irritable mood may not be related to an specific event and may last longer with no specific timepoint of beginning or ending (for further discussion on the different affective constructs please refer to Williams et al., 2018). Accordingly, post-bout mood has frequently been tackled in adults using daily life research (for further details please see the current review by Liao et al., 2015).

The umbrella term 'physical activity' describes different activities such as sports or exercise. Physical activities that occurs in daily life are mostly done for an intended purpose (e.g., in the context of gardening, walking dogs, workplace) and are processed habitually, automatically, spontaneously or incidentally (e.g., cleaning, running to the train; Kanning et al., 2015). We labelled these activities here as "incidental activities" (IA). The reason why a person is physically active depends on his or her motives (e.g., fitness, strengthening, health, enjoyment, competing). Exercise, as a sub-category of physical activity, can be defined as planned, structured and repetitive movement with the main intention to improve physical fitness. Moreover, in contrast to exercise, participation in sports goes along with high physical exertion and with intentions of competition that has official rules and institutional characteristics. Additionally, some definitions imply sports are executed for internal or external rewards and require complex physical skills (Pink, 2008).

To garner insights into how physical activity (i.e., incidental activity, exercise and sports) relates to mood in adolescents, intensive longitudinal data are crucial, since within-subject processes (derived from intensive longitudinal data) are conceptually (Zawadzki et al., 2017), methodologically (Zawadzki et al., 2017), and empirically (Kanning et al., 2013) distinct from between-subject relationships (derived from cross-sectional data). One striking example that emphasizes the importance of this distinction is that people with generally higher physical activity levels showed habitually lower blood pressure (i.e., a negative between-subject correlation), but current higher physical activity coincided with higher blood pressure in everyday life, e.g., when climbing stairs (i.e., a positive within-subject correlation; Kamarck et al., 2003). This example shows that between-subject and within-subject findings are distinct from each other. Using a within-subject perspective to investigate mood is highly recommended since mood is known to fluctuate enormously across time within both healthy and clinical populations (Santangelo et al., 2014).

Ambulatory Assessment (AA) is a state-of-the-art methodology that allows for the gathering of intensive longitudinal data in everyday life (Ebner-Priemer et al., 2012). In particular, physical activity is measured objectively via accelerometers and mood is assessed repeatedly within persons in real time via electronic smartphone diaries (Ebner-Priemer et al., 2012). Consequently, AA has many advantages, such as a high ecological validity compared to laboratory studies ("white coat effect"; Myers & Reeves, 1995), a high accuracy of physical activity measurement compared to retrospective self-reports (Adamo et al., 2009), and no or minimized recall biases compared to self-report methods (Adamo et al., 2009).

In the past decade, a few AA studies have provided evidence that physical activity and mood dimensions are interrelated within adults' everyday lives. For example, studies have investigated whether mood states in everyday life are related to preceding and subsequent physical activity levels (Reichert et al., 2016) or whether there are differential effects for different physical activity types and different mood dimensions (Reichert et al., 2017). This issue has been studied mainly in adults (Reichert et al., 2016; Reichert et al., 2017), and there are few investigations in children (Dunton et al., 2012) and the elderly (Kanning et al., 2015). Thus, the effect of healthy adolescents' natural physical activity behavior on mood dimensions has so far been neglected. There is only one study investigating physical activity and mood in adolescents (Cushing et al., 2018). This lack of research is surprising given the above-mentioned importance of adolescence in physical activity behavior later on in adulthood (Hallal et al., 2006).

However, there is laboratory research on the relationship between physical activity and mood as well as studies on physical activity behavior in adolescents. In the laboratory, adolescents' physical activity was shown to be positively associated with mood dimensions, i.e., energetic arousal and valence and negatively associated with calmness (Szabo et al., 2018). Accordingly, studies found distinct mood responses to sports versus exercises (Masters et al., 2003; Szabo et al., 2018). However, it has yet to be studied whether these findings translate into adolescents' everyday life (ecological validity) and whether there are distinct contextual effects (e.g., based on the type and setting of physical activity).

Despite the converging evidence from AA studies on the real-life association between physical activity and mood dimensions in children (Dunton et al., 2012), adults (Reichert et al., 2016; Reichert et al., 2017) and the elderly (Kanning et al., 2015), the investigation of this psychological mechanism in adolescents has so far been neglected. Thus, we conducted an AA study applying accelerometry in combination with e-diaries on smartphones in 134 individuals aged 12-17 years to investigate specific influences of physical activity on mood in adolescent's everyday life. Based on the empirical findings reviewed above, our main hypothesis was that incidental activity (IA; such as climbing stairs) would increase valence (hypothesis 1) and energetic arousal (hypothesis 2), but also decrease calmness (hypothesis 3) within adolescents. Moreover, we conducted explorative analyses aiming to investigate whether sports (such as soccer and tennis) versus no activity (i.e., not moving at all) and exercise activities (such as jogging and skating) versus no activity (i.e., not moving at all) would show distinct effects on adolescent's subsequent mood. Additionally, we explored the time course of effects.

Materials and Methods

Participants

Adolescents aged 12-17 years were recruited from December 2014 to January 2017 from the URGENCY study (Impact of Urbanicity on Genetics, Cerebral Functioning and Structure and Condition in Young People) in the psychiatric-epidemiological center at the Central Institute of Mental Health in Mannheim, Germany, Adolescents with acute diseases, mental disorders, cardiovascular disorders, or chronic endocrine or immunological diseases were excluded from the study in advance. For detailed information on the recruitment and methods, see (Reichert et al., 2017). Participants received monetary compensation.

We excluded 12 out of 134 datasets due to a large accelerometer non-wear time (i.e., less than ten hours per day (Troiano et al., 2008); 6 out of 134 datasets were excluded because of missing accelerometer data, i.e., lost devices, incomplete recordings (e.g., defect devices or the accelerometer ran out of battery). Furthermore, 3 datasets were excluded due to low e-diary compliance (<30%; Delespaul, 1995). This process led to a final sample size of n = 113 participants (52% male, 48% female). The sample's mean age was 15.02 years (SD = 1.70), and the average BMI was 20.14 kg/m2 (SD = 2.66). There were no meaningful differences between participants/data-sets that were removed and those that were retained for analysis concerning gender ($\chi^2(1) = 0.620$, $p = 0.431$), age (mean included (n = 113) = 15.041, SD = 1.839; mean excluded (n = 21) = 14.407; SD = 1.242; $t(39) = 1.973$; $p = 0.056$), BMI (mean included (n = 113) = 20.143, SD = 2.657; mean excluded (n = 21) = 19.708; SD = 2.883; $t(132) = 0.680$; $p = 0.498$) and socioeconomic status (mean included (n = 110) = 16.646, SD = 2.740; mean excluded (n = 20) = 16.380; SD = 1.877; $t(36) = 0.537$; $p = 0.595$).

Ambulatory Assessment Procedure

Prior to the study, each participant received thorough instructions on how to handle the study devices. Thereafter, the participant's physical activity was monitored objectively via an accelerometer (movisens Move-II or Move-III, movisens GmbH, Germany) in their everyday lives over seven consecutive days. The triaxial acceleration sensors measured IA with a sampling frequency of 64 Hz and a range of ±8 g on the right-hand side of the participants' hips. Participants were instructed to wear the accelerometers during waking hours but not while sleeping. Additionally, participants reported their mood via repeated ratings in e-diaries (Motorola Moto G) in real-time.

For assessing mood, Wilhelm and Schoebi (Wilhelm & Schoebi, 2007) recommend either a two-dimensional construct that is beneficial for a between-subjective perspective (level two) or a three-dimensional model that is beneficial for a within-subject perspective (level one) (Wilhelm & Schoebi, 2007). Wilhelm and Schoebi (Wilhelm & Schoebi, 2007) revealed the following psychometric properties for their three-dimensional scale on the within-person level, i.e., reliability coefficients for valence and calmness: 0.70; and for energetic arousal: 0.77. Therefore, their scales are used in many studies that investigates mood in the everyday life of adults. However, since youths' developmental stages reveal special social (e.g., rules, communication, moral concept and interaction with others) and cognitive skills (e.g., verbal, theory of mind, and self-reflection) that have to be taken into account in the questionnaire structure, we used the first established and validated instrument by Leonhardt et al. (Leonhardt et al., 2016) for assessing mood in adolescents in our study. This instrument is based on the Multidimensional Mood Questionnaire (Wilhelm & Schoebi, 2007) and uses a three-dimensional construct for assessing within-person effects, as recommended by Wilhelm and Schoebi (Wilhelm & Schoebi, 2007). Leonhardt et al. (Leonhardt et al., 2016) validated the mood dimensions valence (items: "content, cheerful, delighted, good, fantastic, unhappy, mad, afraid, miserable"); energetic arousal (items: "concentrated, active, interested, exhausted, tired, faint"); and calmness (items: "rested, pleasant, anxious, stressed, on edge") in youth. These items were presented on seven-point Likert scales with reversed polarity and in a mixed order. Leonhardt and colleagues (2016) showed that this three-dimensional approach is best suited to assess mood in youth on both the between- and within-subject levels (Leonhardt et al., 2016). We calculated psychometric properties for the final (three-dimensional) model using McDonalds Omega (Geldhofet al., 2014) to reveal within and between-subject reliability. The movisensXS smartphone app (version 0.6.3658, movisens GmbH, Germany) triggered e-diary prompts between 16:00 and 20:30 on weekdays (to not disturb pupils) and 9:00 and 20:00 on weekend days and queried for mood levels. Within our sampling schema, participants were triggered based on location; i.e., whenever participants exceeded a distance of 0.5 km, the location-based trigger prompted participants. Methodologically, these triggered e-diaries use an algorithm for real-time detection of situations of interest (i.e., when participants are physically active) to prompt e-diaries exactly at those moments. Thus, this state-of-the-art technology allows for the assessment of a maximum within-subject variance of the parameter of interest in comparison to traditional sampling schemas (triggering, e.g., at random time points; Ebner-Priemer et al., 2012). Additionally, time-based triggers prompted participants at 16:30 and 20:20 (weekdays) or 9:30 and 19:50 (weekend days), resulting in 4-7 prompts/day on weekdays and 8-17 prompts/day on weekends. One prompt followed the other at 37 minutes (minimum trigger interval) at the earliest but not later than 77 minutes (time-out trigger). Participants had the choice to answer the alarm immediately or with a delay of 5, 10, or 15 minutes. Such mixed sampling strategies, e.g., combining location-based and time-based triggers, have been shown to maximize the within-subject variance in the parameters of interest (Ebner-Priemer et al., 2012). After their week of study participation, participants were asked to report the type, time point, and duration of their exercise activities by means of a procedure similar to the Day Reconstruction Method (DRM), which is described in detail elsewhere (Reichert et al., 2016). Participants were shown a digital map (movisens GmbH, Germany) displaying their whereabouts within the study week and were asked to label their sports and exercise locations to report the type of exercise, exercise time points, and durations.

Data Processing

Incidental Activity

To parameterize IA for our main analyses, we first used the software DataAnalyzer (version 1.6.12129, Movisens GmbH, Germany) to compute Movement Acceleration Intensity (MAI, [millig/min]). In particular, raw data (64 Hz) captured from the three accelerometer axes were aggregated to a minute resolution using vector addition. A high-pass filter (0.25 Hz) was used to eliminate gravitational components and artifacts were excluded using a low-pass filter (11 Hz) (for details, see Haaren et al., 2016). Second, to avoid the confounding effects of exercise activity with IA on mood (because both exercise activity and IA were entered into our multilevel model as predictors of interest; see below), we set the incidental activity variable to zero at all time points when participants had been exercising. Third, we aggregated MAI within a 15-minute time frame prior to each answered e-diary assessment because this time frame has been shown to be optimally suited to investigate associations of physical activity and mood (Schwerdtfeger et al., 2010). Fourth, to investigate the time course of the potential effects of IA on mood, we aggregated the MAI within four additional time frames prior to the answered e-diary assessments. Specifically, we aggregated MAI in time frames ranging from 16–30, 31–45, 46–60, and up to 61–75 minutes. To differentiate between-person effects from within-person effects, we centered all incidental activity variables on the persons' mean within the study week.

Exercise

To parameterize exercise activity for our explorative analyses, we used the data derived from the participants' reports on their exercise activity within the study week. In particular, we used the information on the time frame when participants had been exercising to compute a dichotomous variable indicating whether participants engaged in an exercise activity prior to each e-diary prompt [1] or not [0]. To analyze the time course of the potential effects of exercise activity on mood, we created five variables indicating whether exercise activity occurred within the 30, 60, 90, 120, or 240 minutes prior to each e-diary prompt. Thereafter, we used the participants' reports on exercise types to categorize the exercise activities as sports vs. exercise. We defined sports as activities executed in the context of rules and with an international regulatory agency (i.e., basketball, tennis; Bouchard, 2012) and exercise as activity with an increased energy expenditure based on personal interests and needs or with the intent of an improvement of fitness, physical performance, or health (i.e., skating, jogging; Bouchard, 2012). We created categorical variables, i.e., 0 represented "incidental activity", 1 represented "sports", and 2 represented "exercise".

Multilevel Analyses

To identify within-subject relationships between distinct exercise types (sports vs. exercise), IA and the three mood dimensions valence, energetic arousal, and calmness, we conducted multilevel analyses nesting repeated mood ratings (i.e., level 1) within participants (i.e., level 2). We used the statistical software SPSS (version 24, IBM) and set the α-level to 0.05. We calculated intraclass correlation coefficients by estimating three null models for each mood dimension to identify the amount of within-subject variance in our data. We entered the predictors of interest, i.e., exercise (parameterized as a categorical variable, i.e., no activity (i.e., not moving at all) [0], sports [1], and exercise [2]) and IA as a dimensional variable (parameterized as the mean MAI within the 15 minutes prior to each e-diary assessment). To control for conceivable effects of confounding parameters that have been shown to impact either physical activity or mood (Costa et al., 2013; Kanning et al., 2015; Santangelo et al., 2014), we entered age (Costa et al., 2013), gender (Costa et al., 2013), and BMI (Kanning et al., 2015; in level 2, respectively), as well as time and time-squared (Santangelo et al., 2014) (in level 1, respectively) as covariates of no interest into our three models. The predictors time and time-squared were transformed, i.e., we subtracted a value of 9 because adolescents received their e-diary prompts at the earliest time of 9:00. In particular, if an e-diary prompt was triggered at 14:26, the values 5.43 (time) and 29.49 (time-squared) were entered in our model. We added random effects for every level 1 predictor but kept only significant random effects for our three final models (e.g., equation 1). We modeled the data with a variance components matrix and estimated models with full maximum likelihood (Hox, 2009).

<u>Equation 1: Predicting valence (main model 1)</u>

$$\begin{aligned} Y(\boldsymbol{valence})_{ij} \\ &= \beta_{00} + \beta_{01} * age_j + \beta_{02} * gender_j + \beta_{03} * BMI_j + \beta_{10} \\ &* \boldsymbol{non\ exercise\ activity}_{ij} + \beta_{20}^{(k)} * \boldsymbol{exercise^{(k)}}_{ij} + \beta_{30} * time\ of\ day_{ij} + \beta_{40} \\ &* time\ of\ day_{ij}^2 + u_{0j} + u_{1j} * non\ exercise\ activity_{ij} + u_{3j} * time\ of\ day_{ij} \\ &+ r_{ij} \end{aligned}$$

We estimated within-subject effects on level 1. In particular, subscript j refers to participant j, and the subscript i refers to the mood assessment. Accordingly, Y_{ij} represents the estimated level of each mood dimension (i.e., valence, energetic arousal, and calmness, respectively) at the given time i in participant j. The beta coefficients (β) at level 1 represent the intercept as well as the effects of the level 1 predictors IA, exercise activity (where $exercise^{(k)}$ is a dummy variable coding for the three categories of exercise activity), time of the day, and time of the day squared, whereas r_{ij} represents the residuals. Moreover, we estimated between-subject effects on level 2. As stated above, we kept only the random effects showing significance in our final models, represented by u_{ij}. Significant random effects indicated that there is variation in the participants' individual slope estimates around the respective overall mean slope estimates.

Studies investigating physical activity and mood often use short periods for exploring short-term-effects of the predictor (Kanning et al., 2015). However, there is evidence that the effect is of long-term nature (Reichert et al., 2017; Schwerdtfeger et al., 2010). To explore the time course of the effects discovered in our main models, i.e., investigate whether relationships among IA, exercise, sports and mood dimensions are of short- vs long-term nature, we subsequently computed additional multilevel models. For any analyses on the time course of the effects, we used the models specified above (e.g., see equation 2 with modifications highlighted). However, we incorporated one adaptation: We refrained from modeling random slopes but rather considered random intercepts within these additional analyses. In particular, to explore the time course of the effects of IA on mood, we computed 12 models (3*4 for each mood dimension), incorporating IA averaged across distinct time frames prior to the mood ratings (i.e., 16-30, 31–45, 46–60, and 61–75). To explore the time course of the effects of exercise activity on mood, we again computed 12 models (3*4 for each mood dimension) incorporating exercise activities within distinct time frames prior to the mood ratings (i.e., 31-60, 61–90, 91–120, and 121–240). To compare the magnitude of effects, we computed standardized beta coefficients following established procedures (Hox, 2009).

Equation 2: Predicting valence in time course

$$Y(\boldsymbol{valence})_{ij} = \beta_{00} + \beta_{01} * age_j + \beta_{02} * gender_j + \beta_{03} * BMI_j + \beta_{10} * non\ exercise\ activity_{ij}(\boldsymbol{lag\ 30; 45; 60; 75}) + \beta_{20}^{(k)} * exercise^{(k)}{}_{ij}\ (\boldsymbol{lag\ 60; 90; 120; 240}) + \beta_{30} * time\ of\ day_{ij} + \beta_{40} * time\ of\ day_{ij}^2 + u_{0j} + u_{1j} * non\ exercise\ activity_{ij} + u_{3j} * time\ of\ day_{ij} + r_{ij}$$

Results

Descriptive Statistics

The participants' average IA within the study week was 40.86 millig/participant/week (range = 13.32–74.78; SD = 11.87). For the sake of comparison, sedentariness relates to approximately 7 millig and walking to approximately 367 millig (Anastasopoulou et al., 2014). Sixty-eight participants (60%) exercised within the study week resulting in the total of 84 sports and 82 exercise sessions. The participants' mean mood was 5.59 (valence; SD = 0.54), 4.55 (energetic arousal; SD = 0.65), and 5.13 (calmness; SD = 0.63; see Table 1). Furthermore, the ICC was 0.32 for valence (adjudicating an amount of 68% within-person variance), and 0.36 (adjudicating an amount of 64% within-person variance) for both energetic arousal, and calmness, showing good within-person variance for multilevel analyses (Hox, 2009). The participants' overall compliance was 82% (SD = 14.23) in completing the e-diaries. Accordingly, on average, every participant answered 45.12 (SD = 7.8) mood assessments/week.

Table 1: Descriptive Characteristics

	N	Minimum	Maximum	Mean	SD
Age [years]	113	11.50	17.88	15.02	1.70
BMI [kg/m²]	113	14.10	29.40	20.14	2.66
Incidental activity [millig/participant/week]	113	13.32	74.78	40.86	11.87
Valence [mean/participant/week][a]	113	4.10	6.95	5.59	0.54
Energetic arousal [mean/participant/week][a]	113	3.27	6.22	4.55	0.65
Calmness [mean/participant/week][a]	113	3.15	6.63	5.13	0.63
Compliance [percent/week]	113	42.86	100.00	81.95	14.24
Compliance [prompts answered/per day]	113	5.14	13.43	6.37	0.97

[a]Mood (i.e., valence, energetic arousal, and calmness) was assessed on 7-point Likert scales (0–6); for details see method section.

Effects of Incidental Activity on Mood Dimensions

Main Effects – IA

In line with our hypotheses 1-3, our results showed significant within-subject influences for our main predictor of interest, i.e., IA, on all three mood dimensions (valence, energetic arousal, and calmness). IA measured within the fifteen minutes prior to the e-diary prompt was significantly associated with increased valence (beta coefficient = 0.000710; p = 0.002; refer to Table 2) and increased energetic arousal (beta coefficient = 0.000377; p = 0.017; refer to Table 2), but decreased calmness (beta coefficient = -0.000325; p = 0.142; refer to Table 2). In particular, on average, when an adolescent walked instead of remained seated over the 15-minute interval prior to a mood assessment (e.g., 367 millig instead of 7 millig; Anastasopoulou et al., 2014), her or his valence and energetic arousal increased on average by 0.257 and 0.136 (on seven-point Likert scales) within this e-diary entry. However, her or his calmness decreased on average by -0.117 (on seven-point Likert scales) within this e-diary entry.

Our within-subject predictors of no interest, i.e., time of the day and time of the day squared revealed significant associations with valence and energetic arousal but not with calmness (see Table 2). In particular, the association of time of the day with valence and energetic arousal was reverse u-shaped, i.e., participants' valence scores increased from the daily study's start time (at approximately 9:00) to the afternoon (approximately 16:00) and then decreased until the study's end time (at approximately 20:30).

Age, as a between-subject predictor of no interest, showed a significant negative effect on valence and energetic arousal but not on calmness (see Table 2). Sex, as a between-subject predictor of no interest, showed no significant effect on valence and calmness but approached significance in predicting energetic arousal ($p = 0.056$; see Table 2). BMI, as a between-subject predictor of no interest, showed a significant positive effect on valence and calmness but not on energetic arousal (see Table 2).

Table 2: Effect of Physical Activity on Mood: Fixed and Random Effects of Multilevel Model Analysis

		Fixed effects					Random effects			
	Predictor	**Beta**	**Stand. beta**	**SE**	**t-value (df)**	**P-value**	**Variance Estimate**	**SD**	**Wald-Z**	**P-value**
Valence	**Intercept**	5.697*		0.497	11.469	<0.001	0.228	0.038	5.951	<0.001
	Time [hours]	0.064*		0.014	4.701	<0.001	0.001	0.0003	3.610	<0.001
	Time-squared [hours^2]	-0.005*		0.001	-4.412	<0.001				
	Age [years]	-0.074*		0.031	-2.368	0.023				
	BMI [kg/m^2]	0.044*		0.020	2.152	0.036				
	Sex	-0.112		0.100	-1.118	0.263				
	Incidental activity	0.0007*	0.075*	0.0002	3.278	0.002	0.000002	6.9055E-7	3.203	0.001
	Sports (2)	-0.120	-0.029	0.118	-1.015	0.310				
	Exercise (1)	0.258*	0.064*	0.125	2.065	0.039				
	Reference: no activity (0)									
Energetic arousal	**Intercept**	5.390*		0.621	8.677	<0.001	0.350	0.059	5.888	<0.001
	Time [hours]	0.142*		0.016	9.017	<0.001	0.003	0.0007	5.086	<0.001
	Time-squared [hours2]	-0.012*		0.001	-10.080	<0.001				
	Age [years]	-0.102*		0.039	-2.620	0.010				
	BMI [kg/m^2]	0.027		0.026	1.041	0.300				
	Sex	-0.243		0.126	-1.934	0.056				
	Incidental activity	0.0004*	0.033*	0.0002	2.388	0.017				
	Sports (2)	-0.574*	-0.119*	0.130	-4.418	<0.001				
	Exercise (1)	-0.110	-0.023	0.140	-0.787	0.431				
	Reference: no activity (0)									
Calmness	**Intercept**	5.061*		0.590	8.573	<0.001	0.338	0.054	6.292	<0.001
	Time [hours]	0.004		0.015	0.294	0.769	0.001	0.0004	3.287	0.001
	Time-squared [hours^2]	-0.002		0.001	-1.429	0.153				
	Age [years]	-0.060		0.037	-1.629	0.106				
	BMI [kg/m^2]	0.056*		0.024	2.308	0.023				
	Sex	-0.169		0.119	-1.416	0.160				
	Incidental activity	-0.0003	-0.031	0.0002	-1.486	0.142	0.000002	7.9335E-7	2.516	0.012
	Sports (2)	-0.190	-0.043	0.126	-1.511	0.131				
	Exercise (1)	-0.280*	-0.063*	0.134	-2.095	0.036				
	Reference: no activity (0)									

Standardized beta-coefficients are shown for incidental activity, exercise and sports. Random effects are only depicted if significance was observed. Stars (*) indicate significant associations

Time Course of Effects – IA

To investigate how stable associations between IA and mood are distinct across time frames, we analyzed whether IA parameterized within the time frames 1-15 minutes, 16-30 minutes, 31-45 minutes, 46-60 minutes, and 61-75 minutes prior to the e-diary prompt affected the mood dimensions. In Figure 1, the x-axis depicts the time frames, and the standardized beta coefficients from the respective multilevel models are displayed on the y-axis. The associations between IA and both valence and energetic arousal are stable across all investigated time frames. The association between IA and calmness is only significant for the time frame of 16-30 minutes. These results largely support the findings from our main analyses (see 3.2.1 Main effects).

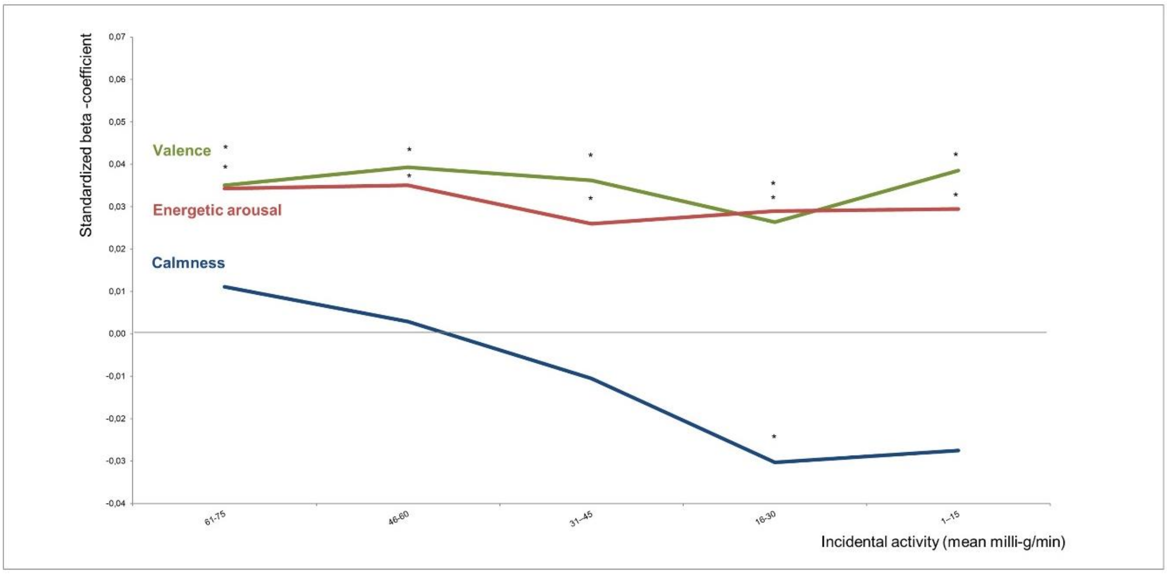

Figure 1: Incidental activity within distinct time frames predicts mood: Effects of incidental activity on mood across subsequent 15-minute intervals prior to the e-diary prompts. The y-axis represents the standardized beta coefficients of valence, energetic arousal, and calmness predicted by incidental activity (x-axis). Significant effects of incidental activity on valence, energetic arousal, and calmness are highlighted (*$p \leq 0.05$).

Explorative Analyses on the Effects of Exercise Activities on Mood Dimensions

Exercise revealed a significant main effect on energetic arousal ($p = <0.001$) and calmness ($p = 0.037$), whereas valence approached the defined significance level ($p = 0.069$).

Sports

Sports were negatively associated with consecutive energetic arousal (beta coefficient = -0.574; $p < 0.001$; see Table 2) compared to no activity (i.e., not moving at all). Translated into practice, when an adolescent engaged in sports vs. did not engage in any exercise activity, her or his energetic arousal decreased on average by -0.574 in one unit (on seven-point Likert scales). However, sports were not associated with valence and calmness (see Table 2).

Exercise

Exercises were positively associated with valence (beta coefficient = 0.258; p = 0.039, see Table 2) compared to no activity (i.e., not moving at all). Translated into practice, when an adolescent engaged in an exercise vs. did not engage in any exercise, her or his valence increased on average by 0.258 in one unit (on seven-point Likert scales). However, exercises were negatively associated with calmness (beta coefficient = -0.280; p = 0.036, see Table 2) compared to no activity (i.e., not moving at all). In particular, when an adolescent engaged in an exercise vs. did not engage in any exercise, her or his calmness decreased on average by -0.280 in one unit (on seven-point Likert scales). Additionally, exercises were not associated with energetic arousal (see Table 2).

Time Course of Effects – Sports and Exercises

To investigate whether associations between exercise activity and mood dimensions are short-term or long-term in nature, we averaged sports and exercises across five time frames prior to the mood ratings (i.e., {1-30}, {31–60}, {61–90}, and {91–120}, and {121–240}). The x-axes of Figures 2-4 depict the five time frames after the exercise activities and prior to an e-diary prompt. The y-axes depict the beta coefficients of the multilevel models predicting the mood dimensions valence (Figure 2), energetic arousal (Figure 3), and calmness (Figure 4).

The findings indicate a significant positive effect of exercise on valence over time (Figure 2) and a negative effect of sports on energetic arousal (Figure 3). In contrast, sports showed no effect on valence and we found no effect of exercise on energetic arousal across all time frames. Exercise was significantly associated with calmness in the time frame {1-30}, but not in any other time frame.

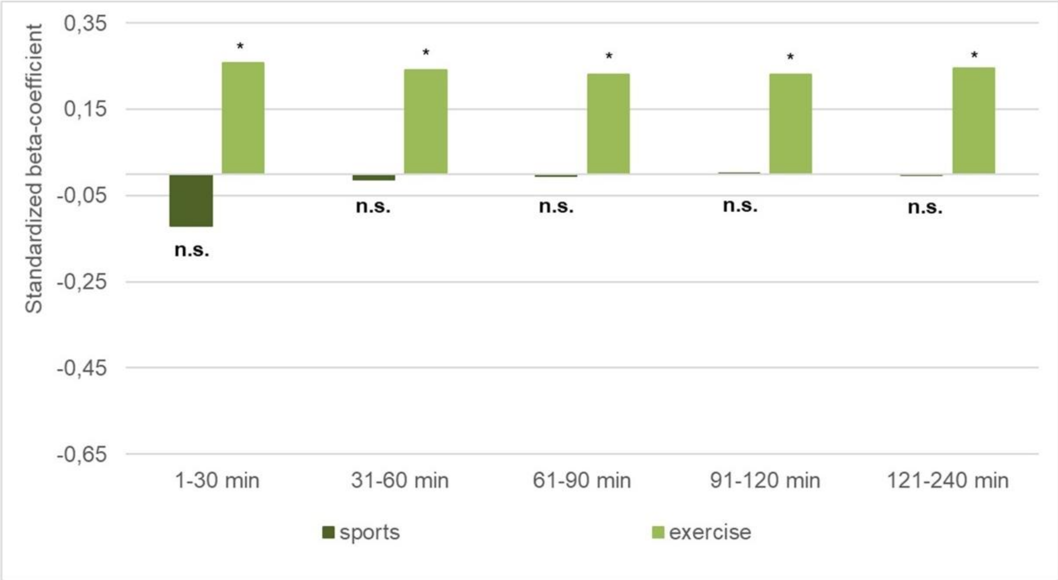

Figure 2: The effect of exercise activities within distinct time frames on valence: Effects of exercise and sports on valence (standardized beta coefficients; y-axis) across five subsequent 30-minute intervals (x-axis) prior to the e-diary prompts. Significant effects of exercise and sports on valence are highlighted (*p ≤ 0.05).

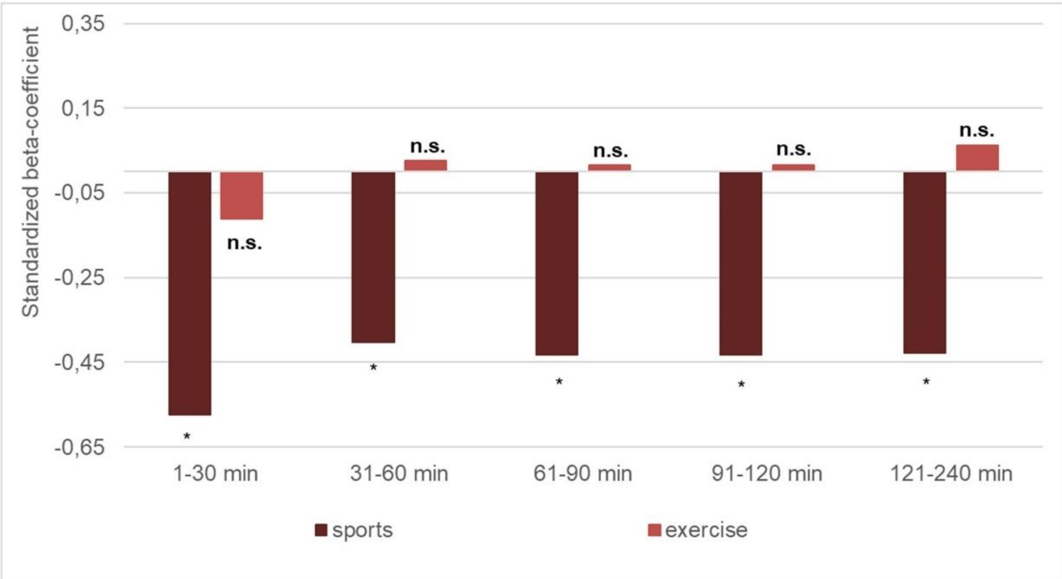

Figure 3: The effect of exercise activities within distinct time frames on energetic arousal: Effects of exercise and sports on energetic arousal (standardized beta coefficients; y-axis) across five subsequent 30-minute intervals (x-axis) prior to the e-diary prompts. Significant effects of exercise and sports on energetic arousal are highlighted (*p ≤ 0.05).

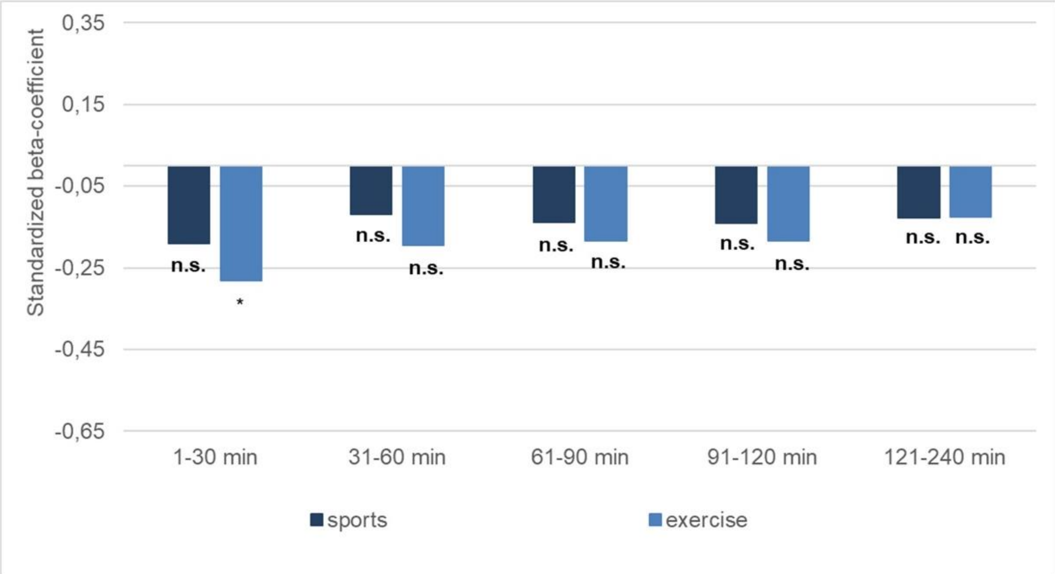

Figure 4: The effect of exercise activities within distinct time frames on calmness: Effects of exercise and sports on calmness (standardized beta coefficients; y-axis) across five subsequent 30-minute intervals (x-axis) prior to the e-diary prompts. Significant effects of exercise and sports on calmness are highlighted (*$p \leq 0.05$).

Discussion

In line with our main hypotheses, our study illustrated that after incidental activity (such as climbing stairs), adolescents felt better and more energized; explorative analyses revealed that after exercise (such as skating), adolescents felt better but less calm; and after sports (such as playing tennis), adolescents felt less energized. To the best of our knowledge, our study was the first Ambulatory Assessment study to investigate the effect of different types of physical activity on subsequent mood in a community-based sample of adolescents. We aimed to consider the differential effects of distinct types of physical activity on subsequent mood. Our findings that IA was positively related to subsequent valence and energetic arousal are in line with those of Hulley et al. (2008), who demonstrated that walking longer distances was related to increases in valence and energetic arousal among 99 children aged 5-10 years over a period of two weeks. In addition, there is converging evidence for a positive within-subject relationship between physical activity and energetic arousal in adult populations (Reichert et al., 2016; Schwerdtfeger et al., 2010) and some evidence for a positive within-subject association between physical activity and valence in adult populations (Reichert et al., 2016; Schwerdtfeger et al., 2010).

Beyond these findings, we identified clear differences in associations between distinct types of exercise activities on subsequent mood; specifically, while adolescents felt better but less calm after exercise, they felt less energized after sports. Our study is the first to focus on the differential effects of distinct types of physical activity on subsequent mood in a real-life setting; consequentially, this makes comparisons with existing literature challenging. Although there have been four studies that showed distinct influences on mood and thus support our findings, these studies were very methodologically very different and focused on affect responses pre, during and after exercises and sports. In particular, our finding demonstrated that sports were negatively related to subsequent energetic arousal is partly supported by Szabo et al. (2018), who found the highest negative affect in competitive situations when comparing positive and negative affect between competitive and training situations among 26 girls performing dancing sports by measuring the affect prior and subsequent to the conditions. Interestingly, even among university students classified as exhibiting a Type A Behaviour Pattern (i.e., TABP), exercising under noncompetitive conditions led to mood increases, whereas competitive conditions did not change their acute mood response at all (Masters et al., 2003). Also supporting our findings, Subramaniapillai et al. (2016) found a decrease in calmness in 31 healthy controls aged 13–20 years subsequent to a laboratory cycling ergometer test. In addition, Cushing et al. (2018) supports our suggestion that different dimensions of affect may have different associations with physical activity. However, due to a lack of studies investigating the post-bout effect of physical activity, exercise, and sports on mood, a comparison with the current literature is challenging and further studies should take the time point of measurement into account (Ekkekakis et al., 2008).

Since adolescents attended school on weekdays, variance in physical activity patterns was limited; for example, pupils usually have to remain seated during lessons and because adolescents were not allowed to use smartphones in school, e-diaries queried for mood from 16:00 to 20:30 on weekdays and 09:00 to 20:00 on weekend days. To account for possible confounds introduced by different assessment ranges, we added weekday vs. weekend as a dichotomous covariate into our main model. However, this did not change the results. We continued to explore possible weekday vs. weekend effects by applying multilevel interaction analyses (weekday vs. weekend* incidental activity and weekday vs. weekend*exercise activity) for all of our main models. Here, we found three significant interaction effects, indicating that sports on weekend days were negatively associated with valence and calmness. Moreover, the negative association of sports with energetic arousal was stronger on weekend days compared to weekdays. These findings further support the conclusions of our study.

Our study provides evidence that a clear differentiation of distinct physical activity types is important for an in-depth understanding of dynamic real-life associations between physical activity and subsequent mood. This information may also help to clarify inconclusive findings in the literature, e.g., studies that did not find any association between physical activity and mood in real life; the missing differentiation of distinct physical activity types might have diluted the effects (Kühnhausen et al., 2013).

Limitations

Some aspects of our study merits further discussion. First, we did not control for winning or losing a match or personal performance in sports. A competitive situation is affected by many parameters such as not playing well, social evaluation, parental pressure, not having fun but experiencing stress, trying to perform up to personal standards and playing difficult technical and tactical shots (Goyen & Anshel, 1998). However, we decided to take all these parameters as a whole, including winning or losing, as being part of competitive sports situations that may affect mood in adolescents. Of course, every one of these factors, e.g., winning or losing a match, may influence participant's mood. Our data may be mixed, i.e., including both "victories" and "failures", which may explain our null findings for the mood dimensions valence and calmness. It should be a subject of investigation in further studies whether additional covariates, e.g., "victories" vs. "failures" or other factors, e.g., exercise intensity, impact adolescents' mood. Second, our sample (age range: 12–17 years) represents different developmental stages in puberty. It is possible that the effects of IA and exercise activity on the mood dimensions differ within these stages. Thus, we explored possible age effects by applying multilevel interaction analyses (age* incidental activity and age*exercise activity) for all of our main models but did not find any significant interaction effects with age. Third, although we parameterized mood as a consequence of exercise activity and IA (i.e., using mood ratings timely following the activities), this constitutes only one aspect of causality. For example, we cannot exclude that hidden third variables might account for our findings. In simple terms, every time adolescents went out to exercise, the weather may have been fine and thus the weather may have accounted for mood changes but not the exercise activity. Physical activity and mood may influence each other in a circular relationship, as suggested by Schwerdtfeger et al. (2010). Further studies should substantiate this hypothesis, for example, using ecological momentary interventions.

Perspectives

To the best of our knowledge, this is the first study investigating the effects of physical activity on mood dimensions in the everyday life of naturally behaving healthy adolescents. In sum, our results revealed the following: after incidental activity (such as climbing stairs), adolescents felt better and more energized; after exercising (such as skating), adolescents felt better but less calm; and after sports (such as playing soccer), adolescents felt less energized. While our explorative findings on exercise activity need to be substantiated in further investigations, we suggest future studies on the association of physical activity and mood to differentiate between distinct types of physical activity to receive unambiguous findings. Translated into practice, our results infer that incidental and exercise activities results in higher post-bout valence compared to sports in competitive settings.

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Paper III

Using e-diaries to investigate ADHD – State-of-the-art and the promising feature of just-in-time-adaptive interventions

Slightly modified version of the published paper

Koch, E. D., Moukhtarian, T. R., Skirrow, C., Bozhilova, N., Asherson, P., & Ebner-Priemer, U. W. (2021). Using e-diaries to investigate ADHD - State-of-the-art and the promising feature of just-in-time-adaptive interventions.

Neuroscience and biobehavioral reviews, 127, 884–898.
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Abstract

Attention-deficit/hyperactive disorder (ADHD) is characterized by symptoms which are dynamic in nature: states of hyperactivity, inattention and impulsivity as core symptoms, and emotion dysregulation as associated feature. Although tremendous work has been done to investigate between-subject differences (how patients with ADHD differ from healthy controls or patients with other disorders), little is known about the relationship between symptoms with triggers and contexts, that may allow us to better understand their causes and consequences. Understanding the temporal associations between symptoms and environmental triggers in an ecologically valid manner may be the basis to developing just-in-time adaptive interventions. Fortunately, recent years have seen advances in methodology, hardware and innovative statistical approaches to study dynamic processes in daily life. In this narrative review, we provide a description of the methodology (ambulatory assessment), summarize the existing literature in ADHD, and discuss future prospects for these methods, namely mobile sensing to assess contextual information, real-time analyses and just-in-time adaptive interventions.

Introduction

One of the first e-diary studies in attention-deficit/hyperactivity disorder (ADHD) titled “get ready, get set, get mad” (Whalen et al., 2006a) nicely summarizes why the methodology of Ambulatory Assessment (AA) fits this disorder so well. Symptomatology in ADHD is highly dynamic (Aase & Sagvolden, 2005), context dependent and burdensome in daily life (Whalen et al., 2006a), these dynamic features are best studied using e-diaries (Trull & Ebner-Priemer, 2013). Different terms have been used for this kind of methodology: ambulatory assessment (AA; Fahrenberg et al., 2007), ecological momentary assessment (EMA; Stone et al., 2002), experience sampling method (ESM; Csikszentmihalyi & Larson, 2014), and real-time data capture (Stone & Broderick, 2007). Even though the terms differ, they have in common the use of computer-assisted methodology to assess self-reported symptoms, behaviors, or physiological processes, while the participant undergoes normal daily activities (Ebner-Priemer & Trull, 2009). Furthermore, they describe the same state-of-the-art method to investigate affective, physiological and behavioral parameters repeatedly in individual's everyday life, mostly using smartphone-apps (e-diaries), and sometimes in combination with wearables (e.g., accelerometers, single sensor systems for electrocardiogram or electrodermal activity, smart watches; Reichert et al. 2020b; Trull and Ebner-Priemer 2013).

The advantages of AA are manifold:

a) Increasing ecological validity (Fahrenberg et al., 2007; Stone & Shiffman, 2010), due to assessments conducted the real life of individuals, without any experimenter bias or distortions of a laboratory setting (i.e., persons who know that they are tested or observed in a laboratory experiment behave different than persons in their natural environment; Greenwood, 1982). In addition, emotional symptoms, and mind wandering in ADHD show ecological utility by capturing the dynamics in daily life (Smyth & Heron, 2014) and not only in the lab or based on retrospective ratings. Hence, laboratory measurements are not always representative of measurements of real life;

b) Minimizing recall biases, often problematic in traditional retrospective paper-pencil-questionnaires (Mehl et al., 2014). With traditional retrospective questionnaires, participants are asked to summarize past feelings, behaviors, and experiences (over the last weeks, months or day; Ebner-Priemer et al., 2006). This active reconstruction process is hard to achieve with accuracy due to recall biases, and can be substantially minimized through real-time AA assessments (Bussmann et al., 2009). More specifically for individuals with ADHD, who commonly experience high levels of inattention often resulting in forgetfulness (Wilens & Spencer, 2010), the advantage of short, real time assessments several times a day instead of long questionnaires, may lessen the burden on the attention and effort required;

c) Accounting for both between- and within-subject differences (Trull & Ebner-Priemer, 2013). Multiple assessments reflect dynamic fluctuations of symptomatology over time, providing a temporal component. This is of special importance, since the translation of between-subject-assumptions into within-subject-assumptions may lead to false interpretations and conclusions. In epidemiological research, this is known as „ecological fallacy“ (Kramer, 1983). Kamarck & Lovallo, 2003 explain this aspect through the association of physical activity and blood pressure: During physical exertion, blood pressure increases (positive within-subject-effect). However, persons with high blood pressure move less (negative between-subject-effect);

d) Examining how contextual factors may influence well-being. For example, smartphones can detect contextual information to identify the impact of real-world social contacts and tasks (i.e., by e-diaries or audio analyses; Whalen et al., 2006a), and/or environmental (i.e., urbanicity, green spaces, pollution, crowdedness) influences on humans using geolocation approaches (Reichert et al., 2020b). Accelerometers can detect physical status (e.g., active, passive) in the everyday life that can hardly be simulated or captured in a lab (Reichert et al., 2020a);

e) Offering objective physiological assessments by wearables (i.e., accelerometers or electrocardiograms), providing an objective measurement of physical parameters such as movement acceleration intensity, level of arousal or heart rate. These physical parameters in combination with subjective self-report ratings can increase validity of the symptoms studied (Adamo et al., 2009; Prince et al., 2008).

With technological progress that has facilitated the use of innovative tools, and the methodological advantages of AA listed above, these real-time assessment methods have been used more often in mental health research in recent years (Brietzke et al., 2019). Measuring fluctuations in feelings and behaviors in the patients' everyday life over time can help us learn more about specific mechanisms of the disorders and may facilitate diagnosis with digital phenotyping (Brietzke et al., 2019). Digital phenotyping is the quantification of human behaviors and functions measured moment-by-moment using personal devices or apps from smartphones in individuals' everyday lives and their personal environments (Baumeister & Montag, 2020; Brietzke et al., 2019; Torous et al., 2016).

When searching leading app-stores, there were a wide range of apps covering mental health issues, with a search in 2019 identifying 1,435 different apps for mental health conditions (Larsen et al., 2019). Even when restricting search criteria to "ADHD-related" apps, 211 different apps were identified in a previous study (Powell et al., 2017). These apps are not all research related or designed to facilitate AA but offer a wide range of support for the concerned parties (i.e., children and adolescents with ADHD and their parents, or adults with ADHD). Powell et al. (2017) identified the top 10 listed apps and proved their suitability in supporting ADHD-related difficulties, family relationships, but also as educational and informational tools. Although, the Food and Drug Administration (FDA) approved a digital therapeutic app for ADHD (Kollins et al., 2020), most apps are not evidence-based and are not supported by empirical evaluation (Larsen et al., 2019).

The main objectives of this review are as follows: First, to increase visibility of existing empirical evidence, we provide an overview of existing AA studies (using, for example personal digital assistants (PDAs) or app-based e-diaries) in children/adolescents and adults with ADHD. To the best of our knowledge, this review is the first focusing on AA studies in ADHD. Second, we will discuss future directions to extend AA methodology by including i) the assessment of contextual information, ii) real-time analyses and iii) just-in-time adaptive interventions (JITAIs; Nahum-Shani et al., 2015).

Methods

To be thorough and transparent in our methodology, we used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; Moher et al., 2009) for guidance regarding reporting of search, extraction and synthesis of results in this review even though this is not a meta-analysis. Figure 1 reports the PRISMA flowchart detailing the screening process.

Search strategy

Only studies using AA designs in ADHD were included in this review, excluding review and meta-analysis studies, and studies with daily life physiological recordings, but no e-diary (e.g. solely accelerometry or blood pressure or EEG). We restricted publication language to English.

To search for relevant AA studies in ADHD, we used Embase 1974 to 2020, week 20; Ovid MEDLINE(R) 1946 to May 19 2020; and APA PSYCHINFO 1806 to May, week 3 2020. The pre-specified search terms were ("Attention-deficit/Hyperactivity Disorder" or "Attention deficit Hyperactivity Disorder" or "ADHD") AND ("Ambulatory Assessment" or "Ecological Momentary Assessment" or "Experience Sampling Method" or "Electronic Diary" or "E-diary" or "Diary Method" or “m-Health” or “mHealth” or “e-health” or “eHealth” or “digital health” or “high frequency mobile monitoring” or “digital monitoring” or “smartphone” or “connected health” or “mobile apps”).

We also scanned references of selected papers to find additional relevant studies, and screened for new studies on the databases published from the end of the systematic search (May 19, 2020).

Study selection

The initial database search identified 265 publications, with 166 unique publications after duplicates were removed. A further screening for type of publication (through the title or other publication details but NOT reading the abstract) yielded to 92 publications across both adult and children/adolescent samples after removing conference abstracts (n=43), reviews (n=17), dissertations (n=3), books (n=10), editorials (n=1). A further 63 publications were excluded at abstract screening stage; n= 58 due to not having used e-diaries, n=1 due to being a conference abstract, n=2 due to not being in an ADHD sample, and n=2 due to not being published in English. At full-text screening stage, we further excluded n=3 publications due to not using e-diaries. After scanning references in relevant papers identified during the search, we included n=5 additional publications fitting the topic, and also included two additional publications published after the initial search was completed. A total of 33 included studies for the narrative review, of which 13 were in adult samples, and 20 in child and adolescent samples. The studies included in this review had clinical or community-based samples recruited on the basis of an ADHD diagnosis or ADHD symptoms (i.e., trait based and not mandatorily a clinical diagnosis), categorized by diagnostic screening questionnaires or self-reports (for detailed information please refer to table 1 and 2).

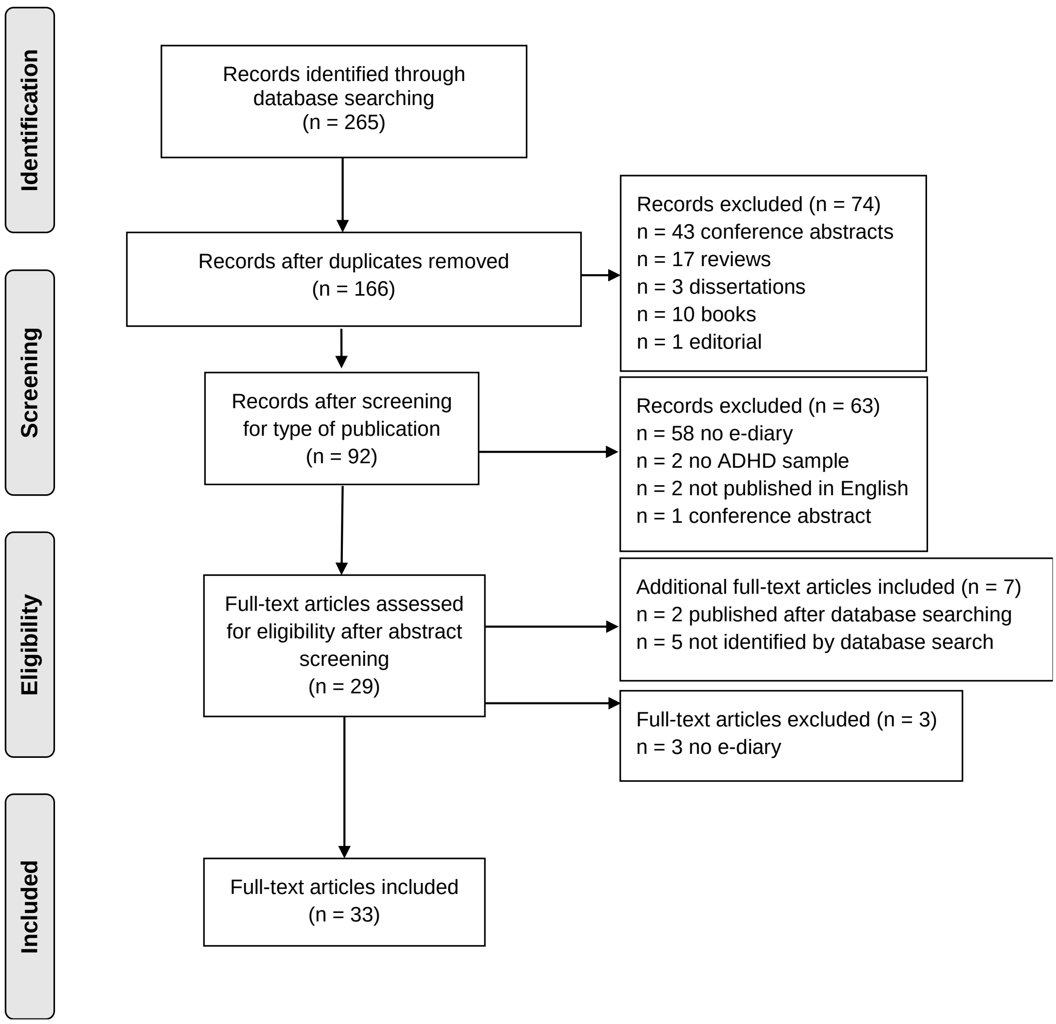

Figure 1: PRISMA Flow diagram

Synthesis of findings

E-diary methods in both child/adolescent and adult samples have primarily been used for two purposes: first, as a symptom and behavior tracker over time and second, as a tool to unravel situational or environmental underpinnings of specific experiences and behaviors such as interpersonal difficulties, drinking and smoking.

Characteristics of child and adolescent studies using AA are briefly summarized in Table 1, and adult studies in Table 2. These tables highlight the heterogeneity of studies with regards to participant sampling and diagnostic methods, sampling schedule and broader study design. We present a narrative summary of these studies below.

Table 1: Characteristics of children and adolescent studies

Study	N included in analyses	Mean age in years (SD)	Sex ratio (%F)	Sample type	Ethnicity	Most comprehensive assessment of ADHD	Intervention	AA duration, sampling frequency	Compliance rate
Babinski et al. (2019)	N=13 n=8 ADHD only n=5 ADHD + depression	ADHD only: 14.1 (1.7) ADHD + depression: 12.8 (0.8)	100%	Adolescent girls with ADHD	80% Caucasian, 20% Hispanic	DBD-I	N/A	8.3 days, twice a day in the week (4pm -9.30pm), four times a day in the weekend (starting 11pm - 9:30pm)	81.7% Mothers: 91.0%, Youth: 84.0%
Factor et al. (2014)	N=64 n=15 ADHD-only; n=27 ADHD-comorbid; n=22 control	9.83 (1.15)	36%	Children with ADHD and children without ADHD and their families	39 Caucasian, 20 African American, 4 biracial, and 1 other	DISC-IV	N/A	Three times a day across 28 days	75.5 %
Fogleman et al. (2016)	N=104 59 children with and 45 children without ADHD	ADHD: 9.61 (1.19) No ADHD: 9.93 (1.27)	ADHD: 36% No ADHD: 51%	Children and their families	63.5% European-American, 26.9% African-American, 3.8% Hispanic-American, 1.0% Asian-American, 4.8% having more than one ethnic background	DISC	N/A	Three times a day across 28 days	Parents: 83.06% (SD = 14.62%; min = 25%, max =100%)
George et al. (2017)	N=151	13.1 (0.91)	48%	Adolescents with heightened risk for mental health problems (80%, at least one conduct disorder symptom)	7.3% White, 23.3% Hispanic, 4.0% African American, 4.7% Native American, 4.0% Asian, with the remaining identifying as belonging to another category	DSM– IV	N/A	30 days, 3 times a day (morning, afternoon and evening)	93%
Leaberry et al. (2017)	N=58	9.53 (1.17)	36%	Children with ADHD and their families. 58.6%, at least one comorbid disorder.	34 Caucasian (58.6%), 18 African American (31.0%), 4 Latino/ Hispanic (6.9%), 2 Biracial (3.4%)	DISC-P	N/A	28 days, 3 times a day	80.81%

Merlo et al. (2018)	N=2	9.17	0%	Children/Adolescents with ADHD	N/A	N/A	Applied Behavior Analysis	Whenever the problem behavior was presented	N/A
Rosen et al. (2013)	Study1: N=11 Study2: n=5 out of N=11	9.45 (1.04)	18%	Children with ADHD and their parents	10 Caucasian, 1 African-American	N/A	N/A	Three times a day across 28 days	86.53 % in parents 84.43 % in children
Rosen & Factor (2015)	N=27 children	9.29 (1.07)	30%	Children with ADHD and their parents	59.3% Hispanic White/Caucasian, 33.3% non-Hispanic Black/African American, 7.4% Hispanic/Latino	DISC	N/A	Three times a day across 28 days	Parents: 1,931 rating points (M = 71.52, SD = 7.30) Children: 1,757 rating points (M = 65.07, SD = 12.71)
Rosen et al. (2015)	N=102 n=56 ADHD n=46 no ADHD	ADHD: 9.61 (1.24) No ADHD: 9.98 (1.28)	ADHD: 38% no ADHD: 46%	Children with ADHD and children without ADHD and their families	63.7 % non-Hispanic White/Caucasian, 25.5 % non-Hispanic Black/African-American, 3.9 % Hispanic/Latino, 5.9 % having more than one racial/ethnic background, 1.0 % Asian/Pacific Islander	DISC	N/A	Three times a day across 28 days	Parents: 82.18 %, SD = 16.0
Slaughter et al. (2020)	N=96 n=53 with ADHD n=43 controls	ADHD: 9.53 (1.19) Control: 10 (1.31)	36% (ADHD) 49% (Control)	Children with ADHD and HC children screened out for ADHD	66.7% Caucasian, 22.9% African American, 4.2% Hispanic/Latino, 4.2% biracial/various ethnic background, 2.1% other	DISC-P	N/A	28 days, 3 times a day	N/A
van Liefferinge et al. (2018)	Study1: N=67 Study2: N=65	Study1: 10.03 (1.23) Study2: 14.03 (1.34)	Study1: 51% Study2: 62%	Children with ADHD from regular primary schools out of a community sample and adolescents with ADHD from regular secondary schools out of a community sample	N/A	DSM-IV	N/A	One week in school holidays by ten prompts per day	N/A

Walerius et al. (2016)	N=84 n=47 children with ADHD n=37 children without ADHD	9.65 (1.18) ADHD: 9.49 (1.10) No ADHD: 9.86 (1.25)	39% ADHD: 36% No ADHD: 43%	Parents of children with ADHD and children without ADHD	53.6 % Caucasian/White, 20.2 % African-American/Black, 4.8 % Latino/Hispanic, 5.9 % biracial, 2.4 % other, 13.1 % did not indicate their racial background	DISC-P	N/A	Three times a day across one week	Parents: 85 % (SD = 14.66 %, min = 35 %, max = 100 %)
Walerius et al. (2014)	N=74 children n=42 children with ADHD n=32 children without ADHD	9.85 (1.19) ADHD: 9.67 (1.16) No ADHD: 10.06 (1.22)	38% ADHD: 31% No ADHD: 47%	Parents of children with ADHD and children without ADHD	64.9% Caucasian/White, 27.0% African American/Black, 4.1% Latino/Hispanic, 4.1% biracial	DISC-P	N/A	Three times a day for 28 days	Parents: 89% of the assessment intervals (SD = 9.24%, minimum = 67%, maximum = 100%) and 88% of the 28 possible IRS intervals (SD = 8.00%, minimum = 57%, maximum = 100%)
Whalen et al. (2002)	N=153 Smokers: 43%	14.5	Smokers: 61% Non-Smokers: 53%	Smoking and non-smoking Students classified into three ADHD levels	52% European American, 16% Asian, 7% Latino, 4% African American, 21% mixed or other	DSM-IV Symptoms subscales from CPRS-R and CASS	N/A	Twice each hour throughout the day and evening for 4 consecutive days	Diary reports were made on approximately 80% of possible occasions
Whalen et al. (2003)	N=27	14.64	15%	27 Students with ADHD and 11 of these were receiving pharmacotherapy	78% Caucasian	DSM-IV	N/A	Every 25 min during waking hours, yielding 25–30 recording opportunities each day over 4 consecutive days	Adolescents: 79% Medicated: 83% Unmedicated: 75%

Whalen et al. (2006a)	N=52 n=27 children with ADHD n=25 healthy controls	10.58 and 10.87	37%	Children with and without ADHD and their mothers	N/A	ADHD segment of the K-SADS	N/A	Seven days with a sampling frequency of 30 ± 5 minutes during non-school hours	Mothers: 91% (ADHD) and 92% (comparison); Children: 89% (ADHD) and 90% (comparison)
Whalen et al. (2006b)	N=52 n=27 children with ADHD n=25 healthy controls	10.58 and 10.87	37%	Children with and without ADHD and their mothers	N/A	ADHD segment of the K-SADS	N/A	Seven days with a sampling frequency of 30 ± 5 minutes during non-school hours	Mothers: 91% (ADHD) and 92% (comparison); Children: 89% (ADHD) and 90% (comparison)
Whalen et al. (2009)	N=109 n=51 children with ADHD n=58 healthy controls	10.46 (1.33)	23%	Children with ADHD taking stimulants or atomoxetine and their mothers; healthy children, and their mothers	Caucasian (78%)	DSM-IV criteria for ADHD on the maternal K-SADS	N/A	Seven days with a sampling frequency of 30 ± 5 minutes during non-school hours	Mothers: 93% (ADHD) and 94% (comparison); Children: 91% (ADHD) and 94% (comparison)
Whalen et al. (2010)	N=109 n=51 children with ADHD n=58 healthy controls	10.46 (1.33)	23%	Children with ADHD taking stimulants or atomoxetine and their mothers; healthy children, and their mothers	Caucasian (78%)	DSM-IV criteria for ADHD on the maternal K-SADS	N/A	Seven days with a sampling frequency of 30 ± 5 minutes during non-school hours	Mothers: 93% (ADHD) and 94% (comparison); Children: 91% (ADHD) and 94% (comparison)
Whalen et al. (2011)	N=109 n=51 children with ADHD n=58 healthy controls	10.46 (1.33)	23%	Children with ADHD taking stimulants or atomoxetine and their mothers; healthy children, and their mothers	Caucasian (78%)	DSM-IV criteria for ADHD on the maternal K-SADS	N/A	Seven days with a sampling frequency of 30 ± 5 minutes during non-school hours	Mothers: 93% (ADHD) and 94% (comparison); Children: 91% (ADHD) and 94% (comparison)

Table 2: Characteristics of adult studies

Study	**N included in analyses**	**Mean age in years (SD)**	**Sex ratio (%F)**	**Sample recruited from**	**Ethnicity or race**	**Most comprehensive assessment of ADHD**	**Intervention**	**AA duration, sampling frequency**	**Compliance rate**
Dan et al. (2016)	N=3	Age 22, 39, 46	67%	University students and employees, all smokers	100% White	Participants provided documentation of their ADHD diagnosis plus self-report scales	Smoking abstinence was rewarded monetarily	Around 25 days with twice daily assessment	92%
Gehricke et al. (2006)	N=10	25 (6.2)	50%	Clinic sample on stimulant medication, smoking at least 10 cigarettes/day for last 5 years.	80% White	DSM-IV from psychiatric interview	2x2 crossover: Placebo patch or transdermal nicotine patch. Usual medication dose or asked not to take their medication.	Four 2-day monitoring sequences, e-diaries 2x per hour plus continual cardiovascular monitoring	N/A
Gehricke et al. (2009)	n=25 abstaining smokers n=27 non-smokers	25.8 (7.3) smokers 28.2 (8.5) non-smokers	76% smokers 67% non-smokers	Clinic sample, medication washed out.	76% Caucasian smokers, 56% Caucasian non-smokers	DSM-IV-TR from diagnostic interview	Double blind placebo patch or transdermal nicotine patch.	Two 2-day monitoring sequences. e-diaries twice per hour, plus continual cardiovascular monitoring	81-86%
Gehricke et al. (2011)	N=15	27.2 (8.6)	13%	Clinic sample, Smokers on regular ADHD medication	87% Caucasian	DSM-IV from psychiatric interview	ADHD medication vs placebo	Two 2-day monitoring sequences. Prompts every 45 (+/-10) min, and self-initiated after smoking.	Min 50% expected (actual not reported)
Halvorson et al. (2020)	N=211	28.0 (4.06)	24%	Pittsburgh ADHD Longitudinal Study; and sampled from the community	67.3% White/European American, 31.8% Black/African American, 0.9% Asian or another race	ADHD Self Report Scale (ASRS; 18 items), and DSM-IV diagnostic interview, or self/informant-report scales or self/informant-report of diagnosis in childhood.	N/A	10 days, with 6-times daily prompting	72%

Knouse et al. (2008)	N=206	19.4 (1.9)	75	College students	72% Caucasian, 25% African American, 1% Hispanic, 1% Asian, 1% unspecified	Self-report rating scales	N/A	7 days; Eight times daily between noon and midnight; random signals	Average of 41.6 usable questionnaires (SD = 11.0)
McKone et al. (2019)	n=62 with ADHD history, n=73 without ADHD history	ADHD history: 27.2 (4.3) No ADHD history: 28.6 (4.0)	ADHD history: 30% No ADHD history: 31%	Pittsburgh ADHD Longitudinal Study; and sampled from the community	69.6% White/European American, 30.4% Black/African American	Mixed: DSM-IV diagnostic interview, or self/informant-report scales or self/informant-report of diagnosis in childhood.	N/A	10 days; self-initiated post-drink questionnaire	758 drinking events were reported, 3 drinking days on average
Mitchell et al. (2014b)	N=17	32.3 (9.7)	47%	Community via advertisement, word of mouth, and referrals from local clinics	58.5%, Caucasian, 35.3% African American, 5.9% Native American	DSM-IV diagnostic interview	N/A	7 days, every 2.5 hours (5-6 per day) during non-smoking periods, and self-initiation before and after smoking.	97%
Mitchell et al. (2014a)	N=4	28.2 (10.1)	50%	Same as above	75% White, 25% Black	Same as above	N/A	Same as above plus continual monitoring with GPS	N/A
Mitchell et al. (2017)	N=20	Treatment 40.6 (6.8); Waitlist 36.2 (6.9)	Treatment: 55% Waitlist: 67%	Same as above	95% White, 10% Black, 5% Native Haw./Pac. Isl.	Same as above	Mindfulness meditation training over 8-weeks	4 days in total (2 at baseline, 2 at 8-weeks); Every 1.25 hr during waking hours (approx. 10 alarms daily)	Mean number of entries was 39.85 (SD = 5.37)
Moukhtarian et al. (2020)	28 ADHD 19 BPD 22 ADHD+BPD 29 Healthy controls	ADHD 38.2(11.7) BPD 35.4(11.4) ADHD+BPD 33.8(13.8) Controls 27.1(5.2)	100%	Clinic sample	N/A	DSM- IV diagnostic interview	N/A	5 days, 8 times daily (semi-randomized)	74.8%

Pedersen et al. (2019)	n=109 with ADHD history, n=102 without ADHD history	27.9 (4.1)	75%	Same as above, but selected for drinking at least once in past month	67.3%, White/European American, 31.8% Black/African American, 0.9% Asian or another race	Same as above	N/A	10 days, with 6-times daily prompting	67%
Skirrow et al. (2014)	n=35 ADHD, n=44 healthy controls	ADHD 28.5 (9.5), Controls 29.0 (10.4)	0%	Clinic sample	N/A	DSM-IV diagnostic interview	N/A	5 days, 8 times daily (semi-randomized)	ADHD 64%, Controls 72.3%

AA studies in children/adolescents with ADHD

In children and adolescents, we grouped the studies into four categories: 1) main ADHD symptoms and associated features, 2) ADHD and related comorbidity, 3) interpersonal relationships, and 4) smoking/alcohol use.

Main ADHD symptoms and associated features in children/adolescents

The most common associated features of ADHD examined in children and adolescents using AA are affective/emotional features. For accuracy in the following overview, we choose the respective terms used by the authors in their papers (e.g., emotional impulsivity, emotional variability, emotional lability, emotional dysregulation). Although these may in some cases refer to overlapping features and problems, wording is not consistent.

Research indicates that children and adolescents with ADHD experience elevated negative affect and emotional lability, and that these associated features are correlated with core ADHD symptoms of inattention and hyperactivity/impulsivity. Whalen et al. (2010) used parental AA report to examine ADHD symptoms and associated features in children with ADHD treated with stimulant medication or atomoxetine, and healthy control children. Findings showed elevated symptoms of hyperactivity/impulsivity, inattention and negative affect in children with ADHD compared to their healthy counterparts, independent of pharmacological treatment (Whalen et al., 2010). Another study used e-diary self-report data from adolescents and their parents to investigate the association between emotional lability and ADHD symptoms in an adolescent community sample with ADHD diagnosis (van Liefferinge et al., 2018). Emotional lability was strongly correlated with hyperactive/impulsive symptoms reported by both adolescents and their parents, with correlations between emotional lability and inattention symptoms being significant for parental report only (van Liefferinge et al., 2018).

In studies focused more strongly on emotional/affective features, AA research has shown that children and adolescents with ADHD experience more variable mood and emotional impulsivity, and that this in turn is associated with impairment. Rosen et al. (2013) investigated the association of mood with ADHD captured with PDAs by children with ADHD and their parents. Parents' e-diary ratings of their children's mood were correlated with parental questionnaire-based ratings of their children's emotional lability and behavioral and emotional distress. Interestingly, in 89.5% of intervals, children rated their mood more positively than their parents (Rosen et al., 2013). In a further e-diary study, Rosen and Factor (2015) investigated children with ADHD and their parents, and found emotional impulsivity to be associated with behavioral and emotional difficulties. In another study, Walerius et al. (2014) found that children with ADHD demonstrated significantly greater functional impairment, measured by the

Impairment Rating Scale (Fabiano et al., 2006) once daily, compared to children without ADHD. Emotional impulsivity, measured three times daily by the PANAS-PR (Phillips et al., 2002), contributed significantly to functional impairment in children with ADHD but not in controls (Walerius et al., 2014).

Other research links emotional variability to aggression in the everyday life of children with ADHD. Slaughter et al. (2020) investigated the impact of AA-derived variability in parental ratings of negative emotion on reactive and proactive aggression measured at two time points (baseline and 6-month follow-up) in children with and without ADHD. Greater negative affect variability was linked to greater reactive aggression at both time points and across both groups, suggesting a unique association between negative affect variability and reactive aggression independent of ADHD status. This indicates that reactive aggression may be common in ADHD due to increased negative affect variability rather than due to their diagnosis. Regarding proactive aggression, both ADHD diagnostic status and AA-derived negative affect variability were significant predictors at baseline, but not at follow-up, and there was no significant interaction between the two predictors. The findings suggest that ADHD and AA-derived negative affect variability might have an independent association with proactive aggression.

Research also indicates associations between ADHD symptoms and digital technology use. George et al. (2018) examined adolescents at risk for mental health conditions, evaluating the relationship between digital technology use (self-report of time spent on social media, texting and on the Internet) recorded three times daily over 28 days, with same-day mental health problems and subsequent conduct problems. Mental health symptoms were reported using established DSM-IV/V criteria scales adapted for AA. There was a high proportion of days that adolescents reported at least one symptom of anxiety (32%), depression (27%), ADHD (28%) or conduct problems (9%). Increases in conduct problems were cooccurred with increases in all aspects of digital technology use. Increases in ADHD symptoms were associated with same-day time spent texting and on social media, but not with time spent on the Internet. In contrast, decreases in anxiety and depression symptoms were associated with increased same-day time spent on texting, suggesting that digital technology use might be used either on asymptomatic days, or as a coping strategy. The overall time spent online also predicted self-regulation problems at 18-month follow-up, as measured by self-report questionnaires, after controlling for ADHD symptoms. These findings support the hypothesis that pre-existing mental health difficulties are linked to more frequent technology use. The authors suggested that future work should focus on clinical and healthy control adolescents, and adopt more objective records of phone use (i.e., device data log) to improve accuracy (George et al., 2018).

Children and adolescents with ADHD and related comorbidity

AA studies indicate that many of the emotional problems described in detail above in children and adolescents with ADHD can be exacerbated in the presence of comorbidity, or may indeed be driven by comorbid symptoms and conditions. A study investigating the relationship between ADHD, comorbidity, and emotional impulsivity in children and their families, found that only children with ADHD and a comorbid disorder (Oppositional Defiant Disorder or Depression) showed significantly more emotional impulsivity, particularly for negative affect (Factor et al., 2014). Hence, emotional impulsivity seems to be associated with comorbidity in children with ADHD, rather than ADHD on its own. This is also shown in another AA study from Leaberry et al. (2017) focusing on children with ADHD alone, and ADHD with comorbid internalizing or externalizing disorders. On parents' perception of intensity and variability of negative affect, results show children with both internalizing and/or externalizing disorders to report greater variability of negative emotions compared to children with ADHD alone. This suggests a unique effect of internalizing and externalizing disorders on variability of negative affect in ADHD. A primary limitation was the very low number of children each comparison group, which reduced the power and generalizability of the study (Leaberry et al., 2017). In a further paper, Rosen et al. (2015) showed no differences in children with and without ADHD regarding emotional lability. However, negative emotional lability was associated with internalizing or externalizing disorders and emotional and behavioral difficulties in both children with and without ADHD (Rosen et al., 2015).

Babinski and Welkie (2019) explored the convergent and discriminant validity of the AA-derived intensity and variability of negative mood in adolescent girls with ADHD alone or with ADHD and comorbid depression. Concordance of AA-derived ratings of negative affect between youth with ADHD and their parents was also examined. Parental and youth reports did not differ for intensity and variability of negative emotion, supporting the convergent validity of AA. Further, girls with ADHD and comorbid depression had increased intensity of negative emotions compared to girls with ADHD alone, supporting the discriminant validity of the method. Due to small sample size, the study used combined ratings of youth and parents, which did not allow the assessment of unique contribution of parental and youth ratings in the intensity and variability of negative emotion (Babinski & Welkie, 2019).

Interpersonal relationships in children and adolescents

Evidence from AA studies suggests that interpersonal relationships can be affected by ADHD symptoms and associated features. Walerius et al. (2016) found parents of children with ADHD to experience more frequent daily hassles (assessed by the Parenting Daily Hassles

Questionnaire (PDHQ); Crnic & Greenberg, 1990) and more intense stress from daily hassles than parents of children without ADHD. Similarly, Whalen et al. (2006b) showed mothers of children diagnosed with ADHD to report increased frequency of anger, sadness and frustration and more frequent disagreement with their children, in contrast to mothers in the control group (Whalen et al., 2006b). Preparatory activities in families with a child with ADHD were more challenging than in families unaffected by ADHD (Whalen et al., 2006a). Mothers of children with ADHD needed more time to prepare their children to leave their homes and reported more stress and anger and less positive mood during these activities compared to mothers in the comparison group. Results showed families with non-ADHD children were more task-oriented in getting-ready activities, while families with ADHD children were more quarrelsome. Furthermore, mothers of children with ADHD reported lower levels of satisfaction and rated perceived ADHD symptoms as limiting family activities (Whalen et al., 2010). Moreover, when examining temporal associations, maternal mood varied systematically with child anger and vice versa (Whalen et al., 2009). In a further study, Whalen et al. (2011) found an association between maternal distress and fluctuations in ADHD behaviors in children. However, this association occurred in both mothers with ADHD children and mothers in the control group (Whalen et al., 2011).

Evidence from AA also suggests that ADHD and associated problems may influence relationship with peers, although there is less research in this subject area. Fogleman et al. (2016) investigated child and parental report of emotional and behavioral difficulties and the relationship between positive and negative affect and peer victimization in children with and without ADHD. By parent's ratings, results show the effect of negative affect on peer victimization to be moderated by ADHD diagnostic status. However, child self-perceived peer victimization showed no association with ADHD (Fogleman et al., 2016).

Using a home-based Applied Behavior Analysis (ABA) intervention, Merlo et al. (2018) investigated the efficacy of the Web Health Application for ADHD Monitoring, recording reductions in ADHD-related behavioral problems of one child and one adolescent with ADHD. Although the app allowed the consistent quantification of frequency, intensity and duration of the targeted problematic behavior associated with ADHD symptoms, its use in ABA interventions is still questionable due to absence of contextual information and potential occurrence of severe escalation of problem behaviors at home, which might require professional's interference. Another barrier to the evaluation of the app efficacy is the use of a case study design, which does not allow the calculation of effect sizes (Merlo et al., 2018).

Smoking/alcohol use in children and adolescents

In an adolescent sample, Whalen et al. (2002, 2003) investigated smoking and non-smoking students with and without ADHD by monitoring their activities (entertainment activities like TV or internet, and achievement-oriented activities like homework and practice), mood, appetitive, alcohol consumption, and smoking using PDAs. Results showed associations between ADHD symptoms and both smoking and drinking behavior. Additionally, adolescents with higher levels of ADHD symptoms reported more sadness, anger, stress, and anxiety, as well as lower rates of well-being and happiness (Whalen et al., 2002). Furthermore, they found higher levels of tobacco use in unmedicated adolescents with ADHD in comparison to medicated adolescents with ADHD (Whalen et al., 2003).

Overview in children and adolescents

Overall, findings show the everyday lives of families with children or adolescents with ADHD to be more challenging than the everyday lives of families with healthy children. ADHD and associated symptoms and comorbidities appear to affect anger, frustration, sadness, stress, anxiety, functional impairment, emotional variability, peer victimization, smoking and alcohol drinking. Findings indicate that children and adolescents with ADHD experience elevated variability and intensity of negative affect on a day-to-day basis compared to control children. Both externalizing and internalizing comorbidities have a unique additive effect on day-to-day variability of negative affect, and day-to-day negative affect variability has a unique association with aggressive behavior independent of ADHD. Increased digital technology may contribute to exacerbation in ADHD symptoms, but is also linked to reductions in anxiety and depression symptoms.

Nevertheless, a major limitation of the current studies is the small sample size and the absence of context measures (the context in which the emotions or behaviors occurred), which means that studies cannot conclude whether children with ADHD or at risk of mental health conditions experience greater negative emotion lability, aggressive behavior, and interpersonal adversity, or experience more provoking events which contribute to the manifestation of these problems. Further limitations that came up in some of the current child AA studies were the lack of control groups and only using parental ratings to investigate children with ADHD. Additionally, some studies chose community samples instead of clinical samples for their investigations, establishing ADHD diagnosis by structured psychiatric interview but not screening for comorbid disorders.

Besides these limitations, AA further demonstrated high compliance rates (83-91%) in both adolescents with ADHD and their parents and high convergent, discriminant and construct validity. This evidence supports the feasibility of the method to measure real-time intensity and variability of mental health symptoms and negative affect in both clinical and community samples.

AA studies in adults with ADHD

In adult samples, we grouped the studies into three categories: 1) main ADHD symptoms and associated features such as emotional dysregulation, executive function, daily functioning, 2) drinking behavior and alcohol consumption, and 3) smoking and effects of nicotine.

Main ADHD symptoms and associated features in adults

Pedersen et al. (2019) and Skirrow et al. (2014) employed e-diaries in a case-control comparison of impulsivity, a main ADHD symptom, and mood lability, an associated feature of ADHD respectively. Pedersen et al. (2019) examined ADHD-related alcohol risk in adults with and without history of childhood ADHD. Five facets of self-reported state impulsivity were measured. The ADHD group showed more variability in three domains of impulsivity (negative and positive urgency and sensation seeking) compared to the non-ADHD group. In an overlapping sample, Halvorson et al. (2020) reported modest to moderate associations between ADHD symptoms and variability (specified as mean squared successive difference) and intensity of the same five facets of impulsive states reported in Pedersen et al. (2019) measured by AA. ADHD symptoms were negatively associated with intensity of “planning” and “persistence”, and positively associated with “negative and positive urgency” and “sensation seeking” (Halvorson et al., 2020). In this context, a unique methodological aspect to investigate variability and instability is to consider the temporal dependency in both, the data assessment and also the data analysis (e.g., standard deviations consider variability but not instability). Although this might be confusing at first glance, excellent guidelines might help with operational definitions and quantification of variability and instability in AA (Ebner-Priemer et al., 2009; Ebner-Priemer & Trull, 2014; Trull et al., 2015).

With a similar case-control design, Skirrow et al. (2014) examined mood lability and the impact of good and bad events on mood in an un-medicated all-male sample without comorbidities. The ADHD group reported more frequent bad events, heightened intensity and instability of irritability and frustration, and greater intensity of anger. The results for positive emotions were equivocal or negative. Bad events significantly contributed to the intensity and instability of negative emotions and showed a stronger influence in the ADHD group. However, covariation for their effect did not eliminate group differences in instability or intensity of mood. In an all-female ADHD, borderline personality disorder (BPD), as well as comorbid ADHD+BPD and healthy sample, Moukhtarian et al. (2021) found no differences in the instability of anger, irritability and sadness in ESM data. However, emotional dysregulation has shown to be similar in instability and intensity in both BPD and ADHD (Moukhtarian et al., 2021).

With the same AA design, Moukhtarian et al. (2020) examined intensity and content of mind wandering in this all-female ADHD group in comparison to a BPD group, a comorbid ADHD+BPD clinical group and healthy controls. Mind wandering items required participants to describe the frequency of different and new thoughts, difficulty keeping to one thought, and thoughts that were off-task. The clinical groups reported heightened mind wandering compared to controls, but no differences from each other. When controlling for depression and anxiety symptoms, significant differences in mind wandering persisted only in the ADHD group compared to all other groups. Negative content of mind wandering, described as daydreaming about something unpleasant as opposed to something pleasant or neutral, was significantly higher in BPD and comorbid ADHD+BPD, which also dissipated when controlling for depression and anxiety. Overall, findings indicate that mind wandering is a core feature in ADHD, but possibly driven by depressive and anxious rumination in BPD (Moukhtarian et al., 2020).

Moving on from basic symptom comparison, Knouse et al. (2008) examined the interaction and impact of ADHD symptoms on mood, distress, current activities, concentration, and social functioning in a non-clinical sample. Overall, hyperactive-impulsive symptoms were unrelated to mood and appeared to be associated with fewer self-reported problems in daily functioning. However, they were related to increased positive mood when subjects were with others but not when alone. On the other hand, higher inattentive symptoms were associated with increased general distress, less positive and more negative mood as well as more concentration problems. Further, the relationship of social contact and positive affect was opposite to that seen in hyperactive-impulsive symptoms; at high levels of inattentiveness, participants reported more positive affect when they were alone than when they were with others.

Mitchell et al. (2017) used e-diaries in a pilot study to assess efficacy of an eight-week mindfulness meditation training program on ADHD symptoms and self-reported executive functioning. Subjects were randomized to the mindfulness or the waitlist group. The treatment group showed reduction in ADHD symptoms, as well as improvement on one of the two executive functioning scales used relative to the waitlist control group. Efficacy of the training program should be interpreted with caution. The trial design had several limitations including small sample size, raters being aware of group status and the comparison group being a waitlist control rather than an active treatment comparison group. Further, mediators, moderators, demographics and comorbidities were not accounted for in the analyses, making the treatment effect unspecific.

Alcohol consumption in adults

E-diaries of alcohol consumption have examined how drinking behaviors relate to underlying characteristics of individuals with ADHD, and the contexts in which drinking behaviors occur. McKone et al. (2019) examined patterns of drinking in participants with and without a history of ADHD, and in relation to self-identified race (White/European American or Black/African American). E-diaries were completed reporting on when, where and with whom drinking occurred, as well as beverage type and speed of consumption. History of ADHD was not associated with any differences in drinking characteristics, and did not interact with race for drinking outcomes. In what appears to be an overlapping participant sample, Pedersen et al. (2019), as described above, monitored self-reported impulsivity through e-diaries, and obtained questionnaire-based indices of problematic drinking in the laboratory. Only for participants with a history of ADHD was variability of self-reported impulsivity associated with reported problematic drinking.

Both studies benefit from a large participant sample, but with a proportion of participants with non-clinical or retrospectively reported diagnosis of ADHD, and lack of objective drinking outcome measures. Additionally, it is unclear why e-diary methods were not used to measure real-time drinking behavior within the same time frame as variability of impulsivity, which makes it unclear whether changes in impulsivity predict problematic drinking behaviors or vice versa.

Smoking and nicotine in adults

High frequency assessments help to clarify the internal contexts in which smoking occurs, and indicate that ADHD symptoms, mood, stress and anxiety interact with smoking behaviors. Gehricke et al. (2009) examined smokers with ADHD blinded to the administration of placebo or stimulant treatment. E-diary ratings included self-reported smoking, smoking urge, stress, and ADHD symptoms. Contrary to authors' expectations, increased smoking urge and frequency was reported under the medication condition (the latter potentially reflecting more reliable reporting). Stress was associated with increased ADHD symptoms when participants were not smoking and/or under the placebo condition. Complementary results are reported by Mitchell et al. (2014b), who assessed smokers with ADHD, and measured self-reported smoking, situational variables, mood, and ADHD symptoms. Smoking occurred more frequently during times of increased negative affect, boredom, stress, worry, and restlessness, and in situations which made participants nervous and frustrated. ADHD symptoms overall did not differ between smoking and non-smoking contexts, although hyperactivity-impulsivity symptoms increased prior to smoking in frustrating situations. ADHD symptoms, negative affect and stress reduced after smoking.

Controlled nicotine exposure studies also indicate that nicotine can lessen ADHD symptoms. This was shown in a crossover study, where abstinent smokers with ADHD refrained from or maintained their usual stimulant treatment, and were blinded to the administration of nicotine or placebo patches (Gehricke et al., 2006). Participants self-reported ADHD symptoms, mood and situational factors for each experimental condition. Nicotine and medication alone or in combination reduced concentration problems, daydreaming and zoning out compared with placebo only. Effects for impatience and perceived control were less consistent. The authors described an absence of nicotine effects on emotion regulation, although analyses were not reported. A reduction in ADHD and associated features under nicotine exposure was also reported in another double-blind placebo-controlled study of abstinent smokers and non-smokers with ADHD (Gehricke et al., 2009). Reports of ADHD symptoms, mood and situational factors were made in each test condition. Nicotine exposure was associated with modest reductions in difficulty concentrating, forgetfulness, restlessness, impatience and impulsivity, anger, nervousness and stress, with no significant interaction with smoker/non-smoker status.

Regarding external context, being in the presence of others smoking, in a bar or restaurant, outside, consuming caffeinated or alcoholic beverages were associated with smoking behavior (Mitchell et al., 2014a). In a very small subsample of their larger study, Mitchell et al. (2014b) described combining behavioral and smoking data with GPS tracking. They showed that smoking was more common closer to home, with greater improvement in ADHD symptoms reported after smoking at work. Studies examining situational factors associated with blinded nicotine or placebo patch exposure report fewer statistically significant results. Gehricke et al. (2006, 2009) reported no significant differences between nicotine and stimulant medication and frequency of locations (e.g., home, school, work), activity (e.g., talk, walk, working), posture (sit, stand, recline), consumption (alcohol, caffeine), and social interactions (e.g., alone, friends, family). However, in the 2009 study smokers with ADHD reported spending more time relaxing than non-smokers when under the nicotine condition.

Dan et al. (2016) examined the potential of e-diaries combined with remuneration for assisting in smoking cessation. Three smokers with ADHD who expressed a desire to quit smoking completed video and e-diary monitoring of CO concentration during an intervention period. Participants were remunerated for meeting specified reductions in CO levels at each assessment, with a thinning of remuneration over time. Participants decreased their exhaled breath CO from a mean of 24 ppm at baseline to a mean of 6 ppm during treatment, but increased again to a mean of 15 ppm at follow-up, one week after completing treatment. Participants rated the smartphone application as effective, convenient, and easy to use.

The available studies have a range of methodological strengths: they examine adults with a well-characterized psychiatric diagnosis of ADHD; use double-blinded administration of nicotine or placebo; and expired CO concentrations to objectively measure smoking exposure. However, these studies uniformly have small samples, lack comparison with healthy controls, and are underpowered to examine comorbidity. Overlapping symptom profiles (e.g. restlessness) can make it difficult to distinguish ADHD and smoking-withdrawal related symptoms (Mitchell et al., 2014a). Studies to date are restricted primarily to self-report and cardiovascular monitoring, with little cross-talk between data collection modalities. For example, the nicotine patch studies indicate increased heart rate, and diastolic and systolic blood pressure during periods of nicotine exposure (Gehricke et al., 2006; Gehricke et al., 2009), but interactions with behavioral outcomes were not examined.

Despite these limitations, the evidence implies that ADHD symptoms and associated problems can reduce in the context of exposure to nicotine, and that stress and ADHD symptoms interact with smoking behavior. This has been interpreted within a framework of smoking as self-medication (Gehricke et al., 2007; Mitchell et al., 2014a), with implications for treatment of smoking behaviors and potentially also symptoms of ADHD.

Future prospects: context, real-time analyses and just-in-time adaptive interventions

Summarizing our findings above, AA has been useful to assess and better understand the dynamic patterns of symptoms, comorbidities and associated features in ADHD. However, limitations that have been identified earlier in this review address sample size, absence of context measure, lack of comparison with healthy controls, being underpowered to examine comorbidity, having overlapping symptom profiles, little cross-talk between data collection modalities, and the question of causality. Besides these limitations, objective measurements (e.g., via accelerometer or electrocardiogram) seem to be absent from the studies summarized above (see also table 1 and 2). This could be due to a real gap in the literature or solely reflect the unspecific search terms we had. However, considering the limitations that have been highlighted, we have to recognize that the advantages AA can offer have not been exploited completely. Hence, in the following section we raise four topics that can be tackled by innovative approaches which already became feasible. Whilst the bulk of this research we describe in these sections has not been completed in individuals with ADHD, the availability of the technology and analysis methods, and their relevance to ADHD populations, opens up a range of important areas that should be studied in detail in the coming decade.

Mobile sensing

First, mobile sensing, is the collection of data from smartphone sensors or wearables. This enables the tracking of user behaviors, such as how often participants spend talking on the phone, writing/receiving messages, or use apps (Kubiak & Smyth, 2019). These sensing parameters can be used as proxies of social behavior and have been used in other clinical conditions to predict, for example, manic or depressive episodes (Ebner-Priemer & Santangelo, 2020). Translated into ADHD context, Schou et al. (2016) showed excessive smartphone use to lead to impulsivity, and daily life impairment, which could be further investigated with regard to whether overall excessive smartphone use or maybe specific apps or calls and messages from specific persons lead to worse ADHD outcomes (i.e., higher inattention, hyperactivity, or impulsivity). In addition, passive monitoring, can help to acquire contextual information using geoinformatics such as GPS (Reichert et al., 2020a). Passive monitoring data can be collected without asking additional momentary questions about social or situational context, thereby potentially reducing participant burden. Furthermore, context information is likely to be of major importance, since behavior is generally context-related (Cook, 2012).

Mobile sensing can also be used to identify areas of risk or triggers for certain behaviors. In one randomized controlled trial, by Gustafson et al. (2014), 170 alcoholic participants were equipped with a smartphone application, that included audio relaxation features, “ask the experts” modules, weblinks, a cognitive behavioral therapy easing distress program, and an online social network assistant. The most sophisticated feature implemented by Gustafson et al. (2014) included the real-time tracking and analyses of patients’ location triggering just-in-time assistance when participants approached their ‘high risk’ drinking spots, such as a favorite bar or a friend´s home where they commonly engaged in drinking behavior. Location data can provide information about current and future drinking risk, and opens up options for examining antecedents and consequences of drinking behavior and the development of interventions.

Similar technology has been developed to monitor smoking and smoking risk. The mobile phone application Q Sense, another mobile phone application, is used as an intervention for tobacco smoking cessation by recording an individual’s location. During an initial assessment period, high-risk locations (places where each participant reports smoking often) are identified by the subjects and these data are combined with more traditional e-diary questions on mood, stress, urge to smoke, current context (e.g., home, working, socializing), and whether others are present (Naughton et al., 2016). With regard to the ADHD literature on nicotine consumption (Gehricke et al., 2009), and given the high comorbidity of ADHD and smoking (McClernon & Kollins, 2008), this feature may allow identification of locations or situations in which ADHD symptoms are associated with nicotine consumption, which could be used in

Just-in-Time Adaptive Interventions with expert instructions or coping strategies, sent to the person's smartphone in the right moment.

Combining GPS-tracking with contextual maps, like Google Maps®, Apple Maps®, Bing Maps® or OpenRouteService, can allow investigation of environmental factors and stressors like crowdedness, green space, noisy streets, urbanicity, indoor/outdoor, and relate them to individual behavior (Reichert et al., 2020a).

In addition, wearables can also be used as mobile sensing devices. These have been applied to covertly or overtly capture a range of risk- and health-related behaviors. For example, cigarette smoking events can be captured by smartwatches which characterize typical hand movements of smoking from the gyroscope and accelerometer (Skinner et al., 2019), and reduce the need for self-report of smoking instances which would otherwise be used to trigger e-diary events or monitoring smoking reduction in quit-smoking interventions. Juarascio et al. (2020) used a wrist worn sensor to measure heart rate variability in real-time, to detect risk of experiencing an emotional eating episode in an ecologically valid setting. Lauckner et al. (2019) combined text message prompts with Bluetooth breathalyzer readings (BACTrack) to monitor alcohol consumption. However, one serious concern is, most of all these sensors are made for the consumer market and only some of them may achieve scientific accuracy (for a detailed discussion please see: German Data Forum (RatSWD, 2020). The accuracy of the devices may also be of special importance to detect differences in movement patterns and to identify bursts of hyperactivity in persons with ADHD (Teicher, 1995). Accelerometers may identify the first occurrence or frequency of bursts in hyperactivity after consumption of ADHD medication. This may be an indicator of how long a drug effect may last, and highlight existing individual differences.

Sampling strategy - Trigger

Second, to measure a behavior of interest, it is crucial to implement an appropriate sampling strategy (Ebner-Priemer et al., 2013; Reichert et al., 2020b). For example, as described previously, preparatory activities for going to school in the morning might lead to impulsive outbursts by children and interpersonal problems (Whalen et al., 2006a; Whalen et al., 2010). However, this episode may be overlooked in study designs using randomly assigned and infrequent e-diary prompts. Fortunately, new technological tools, like mobile sensing combined with real-time AA data and analysis, may provide triggers to measure the episodes of interest. This has been shown using diaries triggered by a range of sensing data, including heart-rate- (Ebner-Priemer et al., 2007), physical activity (Ebner-Priemer et al., 2013), sedentary behavior (Giurgiu et al., 2020) and GPS (Tost et al., 2019).

In one of our studies on the relation between physical activity and mood, we used a GPS-triggered e-dairy. In this study, we tracked distances with acceleration sensors, and provided activity- and GPS-triggered e-diary prompts when participants moved distances further than 500 meters (Reichert et al., 2018; Trull & Ebner-Priemer, 2013). However, this event-based sampling strategy also has limitations, for example whilst it is possible to trigger e-diaries during periods of exercise, it is not practicable to answer questions on smartphones whilst exercising. For detailed information on different sampling strategies in AA, please refer to Fahrenberg et al. (2007) and Shiffman et al. (2007).

Real-time-feedback

Third, combining mobile sensing and real-time analyses with automated real-time-feedback on parameters of interest may help to motivate and change behavior in participants and patients, a methodological approach called Just-in-Time Adaptive Intervention (JITAI; Nahum-Shani et al., 2015). These interventions, being evolvements of ecological momentary interventions (EMI; Heron & Smyth, 2010), are most commonly delivered via smartphone, and have potential to provide simple and cost-effective interventions not only at the most important context, the daily life of the patients, but during the most important situations.

The Q Sense study reported above (Naughton et al., 2016), includes real-time feedback in combination to their mobile sensing. The Q Sense App passively monitors individuals' geolocational context to detect they enter and/or linger for at least 5 min in a high-risk location, previously provided by the subjects themselves. The app sends not only geofence-triggered notification but also delivers support messages tailored to person-specific trigger cues, also collected during the pre-quit assessment stage. In the same vein, the smartphone app in Gustafson et al. (2014), described in detail above, also warned subjects if they have approached a favorite bar. Results of this study showed significantly fewer risky drinking days Gustafson et al. (2014). In ADHD, using the geofence-triggered notification in combination with accelerometry for example could lead to participants getting a signal with an adaptive intervention on their smartphone by reaching a specific threshold or movement pattern by accelerometer, predictive of a hyperactive burst. An idea moving forward to this direction already came up in 2006 by Tryon et al. (2006).

As already mentioned, JITAIs aim to deliver interventions at the right time. If this theoretical advantage is broadly translated into everyday life, the benefits still need to be shown empirically. Initial studies using this methodology are promising (Carpenter et al., 2020; Goldstein et al., 2020; Gustafson et al., 2014; Hébert et al., 2020).

The PROUD trial is an ongoing study and part of the European funded project 'CoCA' to prevent comorbid obesity and depression in patients with ADHD (Mayer et al., 2018). The trial serves as an example for e-diary interventions in ADHD, combining mobile sensing, real-time analyses and feedback. It aims to assess the effect of non-pharmacologic treatments on ADHD and its comorbidities (depression and obesity), in adolescents and adults in a daily life setting. Participants are randomized to either an aerobic exercise intervention, a bright light therapy for 30 minutes daily and continuing treatment as usual, or a control group receiving only treatment as usual. Physical activity and light exposure are monitored via wearable sensors (accelerometers with a light sensor) and symptoms are assessed using e-diaries, with both devices connected via Bluetooth to each other. Participants in all treatment arms take part in four days assessment at baseline pre- and post-intervention measurement (i.e., 8 days of AA), answering questions about their current mood, social context, as well as their mind wandering up to twelve times per day at random intervals.

During the intervention phase, participants of the exercise intervention group are given instructions to perform exercises via a smartphone app. They are guided through their training by exercise videos, motivational reminders, and an overview of their weekly goals. Every evening, the app sends data from both the light sensor and the smartphone, to a centralized server via WIFI connection, that processes data in real time and sends a feedback on activity and exercise parameters back to the participant's smartphone. The feedback generated from sensor data relates to daily steps and movement acceleration and the duration of aerobic and strengthening exercise. The daily feedback is generated automatically in real time, trying to improve participant's motivation and compliance (see Figure 2).

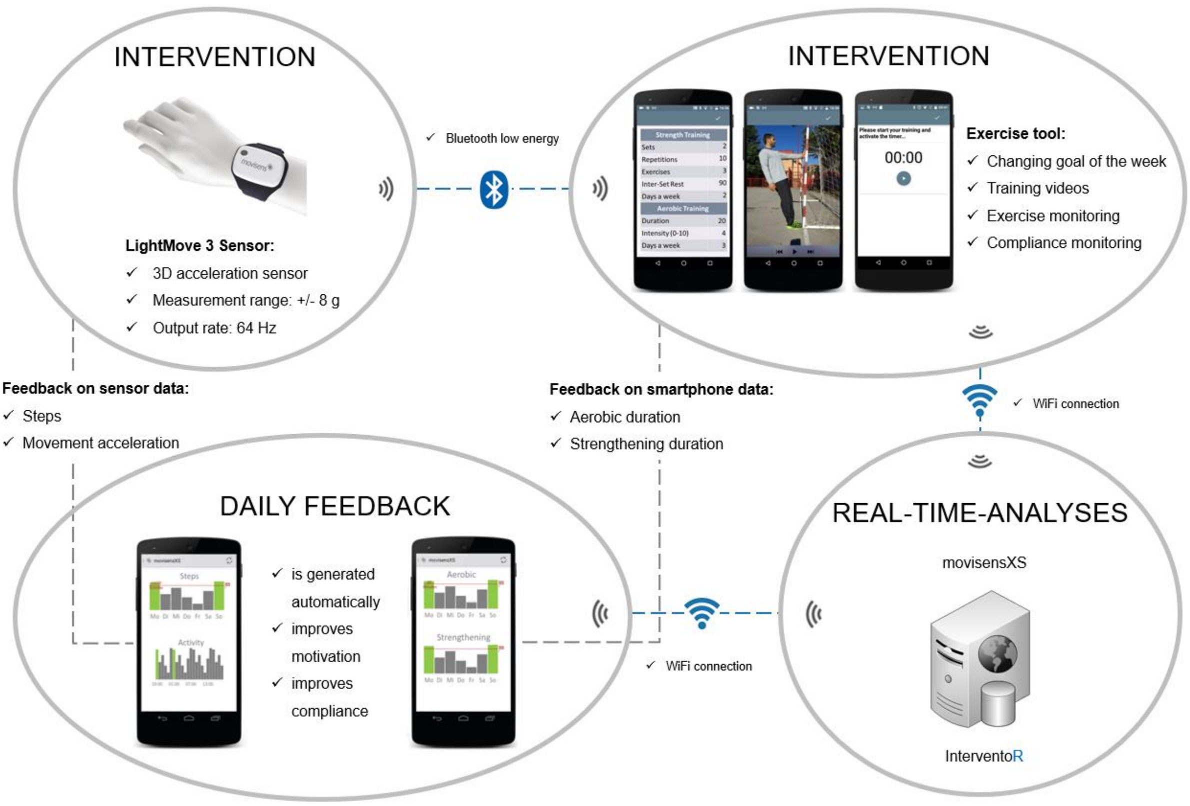

Figure 2: mHealth Feedback System of the CoCA PROUD trial (modified pictures from movisens GmbH, 2021; Pixabay GmbH, 2021)

The open question of causality

The issue of causality is an important challenge in the investigation of psychopathology. Causation concerns how one construct influences another across time and space. For example, we may ask whether fluctuations in mood are an antecedent or a consequence of impulsivity or hyperactivity in patients with ADHD as we see in other variables and patient samples (e.g., mood and exercise; Reichert et al., 2020c). However, although some existing studies accounted for partial causality (e.g., time-lagged within-subject analyses), so far there is no study that could prove the causality of effects in ADHD related symptoms and associated features (e.g., mood and impulsivity or hyperactivity).

One way to investigate causality is to apply JITAIs for target changes one construct or symptom of interest which may be influencing changes in another behavior or function of interest (Reininghaus et al., 2016). For example, if one was interested in potential causal relationships between emotion regulation and impulsivity, one may set up an intervention program prompting participants at multiple random times across the day to use emotion regulation strategies. Additionally, we can assess impulsivity before and after these real-time interventions. Because the prompted emotion regulation intervention is most likely independent of hidden third variables, this approach might constitute a step towards proving causality for consequences of emotion dysregulation. For example, the co-occurrence of symptoms of impulsivity and emotion dysregulation may be due to a third unmeasured factor (drinking coffee, contact with peers). Randomly prompted interventions and resultant changes in other symptoms are less likely to be affected by additional unmeasured external influences. The combination of continuous sensing, real-time analyses and real-time feedback may therefore also help to better understand temporal causality across psychopathological constructs in patients with ADHD.

Conclusion

Investigating ADHD symptoms and comorbidities using the AA methods can help us to understand underlying mechanisms of ADHD and capture dynamic patterns of behavior that cannot be investigated in physicians' office, laboratory or clinical settings (Ausiello & Lipnick, 2015). In combination with clinical interviews and screenings, e-diaries can support psychiatric practices and improve the diagnosis due to complementary assessment of feelings and behaviors in the everyday lives of patients, revealing fluctuations over time that could be relevant in a clinical context. Providing just-in-time-adaptive interventions is now becoming technologically feasible. Hence, the opportunity to implement interventions that are fitting participants' inter- and intra-individual needs and their everyday life should be a major focus in future research.

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Paper IV

The Dynamical Association between Physical Activity and Affect in the Daily Life of Individuals with ADHD

Slightly modified version of the published paper

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Abstract

Exercise interventions in mental disorders have evidenced a mood-enhancing effect. However, the association between physical activity and affect in everyday life has not been investigated in adult individuals with ADHD, despite? being important features of this disorder. As physical activity and affect are dynamic processes in nature, assessing those in everyday life with e-diaries and wearables, has become the gold standard. Thus, we used an mHealth approach to prospectively assess physical activity and affect processes in individuals with ADHD and controls aged 14–45 years. Participants wore accelerometers across a four-day period and reported their affect via e-diaries twelve times daily. We used multilevel models to identify the within-subject effects of physical activity on positive and negative affect. We split our sample into three groups: 1. individuals with ADHD who were predominantly inattentive (n=48), 2. individuals with ADHD having a combined presentation (i.e., being inattentive and hyperactive; n=95), and 3. controls (n=42). Our analyses revealed a significant cross-level interaction (F(2, 135.072)=5.733, p=0.004) of physical activity and group on positive affect. In details, all groups showed a positive association between physical activity and positive affect. Individuals with a combined presentation significantly showed the steepest slope of physical activity on positive affect (slope_inattentive=0.005, p<0.001; slope_combined=0.009, p<0.001; slope_controls=0.004, p=0.008). Our analyses on negative affect revealed a negative association only in the individuals with a combined presentation (slope=-0.003; p<0.001). Whether this specifically pronounced association in individuals being more hyperactive might be a mechanism reinforcing hyperactivity needs to be empirically clarified in future studies.

Introduction

Attention-deficit/hyperactivity disorder (ADHD) is a neuropsychiatric disorder that is present in 3–5% of school-age children (Polanczyk et al., 2014). Moreover, in approximately 50% of children with ADHD the disorder persists into adulthood (Sobanski & Alm, 2004). In addition to the main symptoms (i.e., inattention, hyperactivity, and impulsivity), ADHD is associated with comorbidities and cooccurring symptoms (e.g., affective instability, mood dysregulation, depression and negative affect (Mikolajewski et al., 2013), worsening the outcome of ADHD (Katzman et al., 2017). Physical activity has been shown to improve affective states in population (Bohnert et al., 2009; Gauvin et al., 1996; Gawrilow et al., 2016) and patient samples (Emmerson, 2010; Kanning et al., 2013). However, only a few studies, predominantly with children and adolescent samples, have investigated the association between physical activity and mood in everyday life in individuals with ADHD with the Ambulatory Assessment (AA) method (Emmerson, 2010; Gawrilow et al., 2016). Herein, an absence of physical activity has been shown to be associated with depressed affect, and increased physical activity has been shown to improve affect and executive functioning in children with symptoms of ADHD (Gawrilow et al., 2016), children diagnosed with ADHD and children without ADHD diagnosis (Emmerson, 2010). Additionally, in comparison to sedentary classroom-based interventions, physical activity interventions have been shown to be more effective in reducing moodiness (i.e., temper outburst; cries often and easily; and mood changes quickly and drastically) in children at risk for ADHD (Hoza et al., 2015). Using a nested case-control design, further findings have shown both a unidirectional association between motor activity and positive mood and bidirectional associations between motor activity and energy level as well as motor activity and sleep duration. Hence, the authors concluded interventions that focus on motor activity are more effective in treating depressed mood than other approaches (Merikangas et al., 2019).

ADHD symptomatology and affective states are dynamic in nature (Aase & Sagvolden, 2005). Due to a lack of technology, capturing dynamic processes in the past was challenging. With the AA method, it became feasible to measure dynamic associations in real time by monitoring physical states, behaviors, and feelings in persons' everyday life (Trull & Ebner-Priemer, 2013). The AA method assesses both between-subject and within-subject effects, depicting fluctuations over time (Kanning et al., 2015; Trull & Ebner-Priemer, 2013). Moreover, accelerometers show higher validity of objective physical activity measurements than subjective self-ratings, and e-diaries are advantageous in asking for feeling states (e.g., positive affect and negative affect) several times a day (Adamo et al., 2009; Ebner-Priemer et al., 2012).

Here, we investigated the association between physical activity and positive / negative affect regarding within-subject processes in adolescents and adults with ADHD. Exploratively, we further divided the sample of individuals with ADHD according to the predominant symptoms (i.e., predominantly inattentive presentation and the combined presentation of being both inattentive and hyperactive) due to the suggestion of treating the predominant symptoms as distinct disorders in the literature (Milich et al., 2001) and compared the groups to controls. We expected steeper slopes in positive and negative affect in the individuals with ADHD due to worse baseline affect (Breaux et al., 2020).

Materials and Methods

Within the CoCA PROUD trial (Mayer et al., 2018), we investigated individuals with ADHD and control participants between 14 and 45 years of age with the AA method in four European clinical sites at Frankfurt, Nijmegen, London, and Barcelona. Out of the 207 individuals with ADHD who were randomized to an intervention afterward, we received e-diary and/or acceleration baseline data from 236 participants (n=183 individuals with ADHD and n=53 controls). We excluded 5 participants due to completely missing either e-diary or acceleration data; 40 participants were excluded due to an e-diary compliance rate below thirty percent; 4 participants were excluded due to missing demographic data; 1 participant was excluded due to an inpatient stay; and 1 participant was excluded due to a missing diagnosis. Hence, for the analysis, we solely included baseline data and used a subsample of 185 participants (n=48 individuals with a predominantly inattentive presentation; n=95 individuals with a combined presentation; n=42 controls; n=100 females; n=36 adolescents). The remaining participants had an e-diary compliance rate of 77% (predominantly inattentive presentation, SD=18.04), 76% (combined presentation, SD=17.29), and 87% (controls, SD=12.72). Individuals with ADHD met all diagnostic criteria for ADHD according to the Diagnostic and Statistical Manual of Mental Disorders (DSM-5; American Psychiatric Association, 2013), and controls were only recruited in Frankfurt and London. Accelerometer data were analyzed by the software DataAnalyzer (movisens GmbH, version 1.6.12129) to compute the movement acceleration intensity [millig/min]. A smartphone app (movisensXS; movisens GmbH) provided twelve random e-diary prompts per day for four days (i.e., baseline assessment), measuring positive affect with six items (i.e., cheerful, satisfied, energetic, enthusiastic, happy, and relaxed) and negative affect with seven items (i.e., insecure, lonely, anxious, low, guilty, sad, and irritated) as a short version (Myin-Germeys et al., 2003) of the Positive and Negative Affect Scale (PANAS; Watson & Tellegen, 1985). Responses were rated on seven-point Likert scales, and we computed the sum score out of the positive (range: 6–42) and negative affect items (range: 7–49). We combined the accelerometer and e-diary data by using the software DataMerger (movisens GmbH, version 1.6.3868). Statistical analyses were conducted using SPSS software (IBM; version 25). For identifying timeframes with higher and lower physical activity, movement acceleration intensity (millig/min) was person-mean-centered and aggregated into 10-min intervals prior to each e-diary assessment (Bossmann et al., 2013; Kanning et al., 2013, 2015; Reichert et al., 2016). We used multilevel analyses to estimate the within-subject effects of repeated physical activity ratings on positive affect and negative affect. To investigate our expectation of a steeper slope in the ADHD groups, we built a mixed model that included the main effects of physical activity (level 1) and the groups (i.e., predominantly inattentive presentation, combined presentation, and controls, level 2) and the corresponding interaction between them. The variables time, time^2 (level 1), age, BMI, and gender (level 2) served as covariates to control for confounding variables. Physical activity, time and time^2 were also implemented in the random part of our model. To understand and interpret the interactions, we computed simple slopes of physical activity within each group (predominantly inattentive presentation, combined presentation, and controls) and compared them among each other.

Results

The two patient groups did not differ regarding gender, age, BMI and comorbid depression scores (shown in Tab. 1). However, the group with a predominantly inattentive presentation differed significantly from the controls in the variables gender (p=0.042) and age (p=0.002) and also the group with a combined presentation differed from the controls in age (p<0.001) and BMI (p=0.017; shown in Tab. 1).

Table 1: Descriptives – mean values and standard deviations

Category	inattentive		combined		controls	
Gender	16 males	32 females	46 males	49 females	23 males	19 females
Age	24.75 (8,18)		26.65 (7.92)		20.29 (4.70)	
BMI	24.89 (5.86)		25.46 (5.94)		22.99 (4.41)	
Depression (IDS-C30; range: 0-84)	13.06 (8.66)		15.04 (9.60)			
Positive affect (range: 6-42)	24.39 (6.01)		24.76 (5.17)		31.38 (4.52)	
Negative affect (range: 7-49)	11.85 (4.54)		13.44 (6.28)		8.92 (1.92)	

In the analysis of the whole sample (individuals with ADHD, those with predominantly inattentive presentations, those with combined presentations, and controls), the results show a significant interaction effect of physical activity x group on positive affect (F(2, 135.072)=5.733, p=0.004; shown in Tab. 2), suggesting a differential effect of physical activity over the groups. The calculation of simple slopes of physical activity within each group revealed significant effects of physical activity in all three groups (slope_inattentive=0.005247, p<0.001; slope_combined=0.009138, p<0.001; slope_controls=0.003753, p=0.008). In other words, in the ten minutes after high levels of physical activity, positive affect was significantly increased. To give a more practical example, by walking (i.e., 367 millig) instead of sitting (i.e., 7 millig) ten minutes prior to the mood assessment, positive affect was increased in the combined presentation group by 3.2 points. In detail, the group with combined presentation had the steepest positive slope and differed significantly from the group with predominantly inattentive presentation (p = 0.025) and controls (p = 0.002; shown in Fig. 1a), whereas the group with predominantly inattentive presentation and controls did not show a significant difference (p = 0.449). Confirming our hypothesis, the association between physical activity and positive affect remains larger for individuals with ADHD than for the controls by comparing the slopes.

Table 2: Main and Interaction Effects (F-test)

	Category	Numerator df	Denominator df	F value	P value
Positive Affect	**Intercept**	1	181.967	109.449	<0.001
	Time [hours]	1	162.557	21.881	<0.001
	Time-squared [hours^2]	1	162.405	16.513	<0.001
	Physical Activity pmc [millig]	1	136.292	65.475	<0.001
	Physical Activity mean [millig]	1	177.542	0.974	0.325
	Age [years]	1	177.270	9.237	0.003
	BMI [kg/m^2]	1	179.328	1.113	0.293
	Gender [male]	1	177.484	2.042	0.155
	Group	2	177.610	18.945	<0.001
	Physical activity x group	2	135.072	5.733	0.004
Negative Affect	**Intercept**	1	176.516	12.632	<0.001
	Time [hours]	1	181.716	1.347	0.247
	Time-squared [hours^2]	1	181.377	3.083	0.081
	Physical Activity pmc [millig]	1	127.224	3.270	0.073
	Physical Activity mean [millig]	1	170.871	1.565	0.213
	Age [years]	1	172.858	1.110	0.294
	BMI [kg/m^2]	1	176.287	0.433	0.512
	Gender [male]	1	173.848	5.520	0.020
	Group	2	175.609	8.938	<0.001
	Physical activity x group	2	124.037	3.020	0.052

Furthermore, we found an interaction effect of physical activity x group on negative affect (F(2, 134.037)=3.020, p =0.052), which in fact was statistically nonsignificant. Nevertheless, we gave it the benefit of the doubt and decided to include it in the model, which is in line with statements of the American Statistical Association about *p* value principles (Wasserstein & Lazar, 2016). The calculation of simple slopes of physical activity within each group provided evidence of a differential effect of physical activity over the groups on negative affect (slope_inattentive=0.000300, p=0.801; slope_combined=-0.003040, p=0.001; slope_control=0.000750, p=0.526). In detail, the group with combined presentation had a significant negative slope and differed significantly from the group with predominantly inattentive presentation (p = 0.023) but not from the controls (p = 0.115; shown in Fig. 1b).

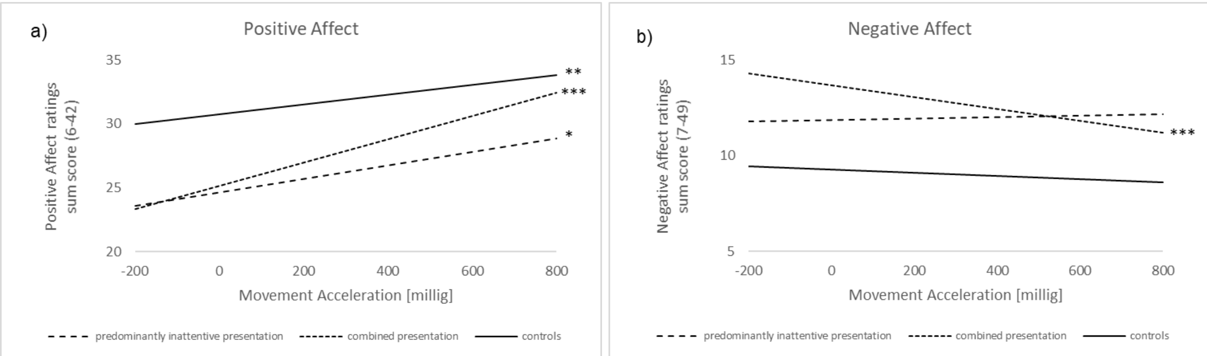

Figure 1: a. Positive affect and b. negative affect slopes in the ten minutes after low, average and high levels of physical activity on a person's mean score. Positive and negative affect were measured by 7-point Likert scales (positive affect range: 6–42; negative affect range: 7–49; y-axis) depending on low levels (i.e., below the person's mean score [-200]), average levels (i.e., at the person's mean score [0]), and high levels (i.e., above the person's mean score [800]) of physical activity (i.e., person-mean-centered in millig; x-axis). Significant slopes are identified with *P ≤ 0.05, **P ≤ 0.01, and ***P ≤ 0.001.

Discussion/Conclusion

Our results point toward a specifically pronounced association between physical activity and affect in individuals with ADHD having a combined presentation of symptoms (i.e., being inattentive and hyperactive). This is evidenced by a significantly steeper slope on positive affect and a significant effect on negative affect only in this group. In addition, the predominantly inattentive group and the controls showed a positive association between physical activity and positive affect.

For controls, our results are in line with previous literature, that showed physical activity improves affect in adolescents (Gawrilow et al., 2016), that structured free time and sports activities have a positive association with positive affect in adolescents (Bohnert et al., 2009), and that physical activity increases positive affect in a community-based sample of women attending fitness classes (Gauvin et al., 1996). However, our results are not in line with a previous study that investigated the associations between physical activity and mood using the AA method in children with ADHD (Emmerson, 2010). In this previous study, physical activity had a larger positive impact on mood in children without ADHD than in children with ADHD, which is contrary to our findings. However, physical activity was assessed by self-reports with e-diaries, which are known to have limited reliability (Adamo et al., 2009). In line with our findings, Hoza et al. (2015) showed physical activity to be effective in reducing moodiness in children at risk for ADHD compared to controls, with a tendency toward larger improvements in children in the ADHD-risk group. Additionally, in a patient sample with bipolar and major depressive disorders, motor activity was shown to decrease depressed mood (Merikangas et al., 2019), confirming our results for negative affect in the increased hyperactivity sample.

One explanation for not finding an association between physical activity and negative affect in two groups (i.e., predominantly inattentive and controls) may be due to very low baseline negative affect scores, which are hard to improve. This null finding for negative affect in controls is also shown in previous literature that did not find an association between physical activity and negative affect, but did find a significant increase in positive affect in their study by using accelerometers and e-diaries (Schwerdtfeger et al., 2008; Wichers et al., 2012). Additionally, in a patient sample with eating disorders, physical activity was shown to be associated with positive emotional states, but not negative emotional states, in a daily life study (Vansteelandt et al., 2007).

To conclude, we prospectively investigated, how physical activity and affect fluctuates within adolescents and adults with ADHD and controls in everyday life over time by using e-diaries and accelerometers. Statistically, we found that individuals with ADHD with a combined presentation of the symptoms showed the strongest beneficial effects on positive and negative mood. Since there is evidence that the improvement of comorbidities and co-occurring symptoms has a positive effect on the outcome of ADHD symptoms (Katzman et al., 2017), improving affect in individuals with ADHD may also positively affect other ADHD-related symptoms. Whether this specifically pronounced association in individuals being more hyperactive might be a mechanism probably reinforcing hyperactivity needs to be empirically clarified in future studies.

Future studies should also take the following limitations of our analysis into account: a) we did not control for other comorbidities and b) we did not control for the type of activity (i.e., incidental physical activity, exercise, or sports).

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General Discussion

The present work investigated associations between physical activity and mood in individuals with ADHD and in healthy controls, as well as in a community-based adolescent sample, using the Ambulatory Assessment method. Summarizing the findings above, we found the following:

1) Valence and energetic arousal are positively related to, and calmness is negatively related to, subsequent incidental physical activity (i.e., **mood is related to subsequent incidental physical activity** in healthy adolescents; Koch et al., 2018);
2) Healthy adolescents feel better and more energized after incidental physical activity (e.g., climbing stairs); they feel better but less calm after exercise (e.g., skating); and they feel less energized after sports (e.g., playing tennis) (i.e., **incidental physical activity, exercise, and sports are related to subsequent mood** in healthy adolescents; Koch et al., 2020);
3) Ambulatory Assessment is a useful method by which to understand the dynamic patterns in ADHD that cannot be investigated in a physicians' office, laboratory or clinical settings. **Ambulatory Assessment has been shown to help psychiatric practices** improve their diagnoses by revealing fluctuations over time that could be relevant in a clinical context (Koch et al., 2021);
4) Physical activity improves positive affect in individuals with ADHD and in healthy controls; and physical activity improves negative affect in the subgroup of ADHD patients who are more hyperactive than others (i.e., **physical activity is related to subsequent mood in individuals with the combined presentation of ADHD symptoms**; Koch et al., 2022).

To summarize the limitations of prior research as well as those from our (Ambulatory Assessment) current research on physical activity and mood: studies in the past (a) showed a lack of power regarding both sample size (between-subject level) and the number of e-diary ratings (within-subject level; Liao et al., 2015); (b) utilized community samples instead of clinical samples for the study of mental disorders (Koch et al., 2021); (c) lacked control groups in clinical studies (Koch et al., 2021); (d) did not control for comorbid disorders in clinical studies (Koch et al., 2022); (e) lacked different time frames to show the duration of an effect (Kühnhausen et al., 2013); (f) lacked context measures (Koch et al., 2021); (g) included little discussion of data collection modalities (for an overview see Koch et al., 2021); (h) utilized self-report assessments instead of objective measurements (e.g., via accelerometer or electrocardiogram; for an overview see Koch et al., 2021); (i) treated physical activity intensities as categorical variables (e.g., light, moderate, and vigorous physical activity) instead of as dimensional variables (i.e., movement acceleration intensity; Dunton et al., 2014; Ebner-Priemer & Trull, 2009); (j) left open the question of causality (Reichert et al., 2020); (k) did not consider the stage of puberty in composing their adolescent samples (Koch et al., 2018, 2020); (l) made no differentiation between weekdays and weekend-days (Koch et al., 2018); and (m) encountered sampling difficulty due to subjects not being able to answer questions on smartphones (e.g., mood) while exercising.

The four papers of this work already provided detailed discussions on the results. Hence, the following general discussion will focus instead on lessons learned and experiences gathered during the clinical trials. Furthermore, the future prospects and needs of Ambulatory Assessment research, especially with regard to technical and methodological opportunities, will be considered.

Subject 1: State of science: Innovative technical and methodological features in Ambulatory Assessment research

The first and second paper of this work emerged from the URGENCY study (Impact of Urbanicity on Genetics, Cerebral Functioning and Structure and Condition in Young People) at the psychiatric-epidemiological center (PEZ) of the Central Institute of Mental Health in Mannheim, Germany. The methodological innovation of this study in Ambulatory Assessment was the use of GPS-triggered e-diaries to measure episodes of low and high physical activity in daily life (Koch et al., 2018, 2020; Reichert et al., 2017; Reichert et al., 2016). Specifically, the GPS trigger released an e-diary prompt when a distance of 500 meters was exceeded. These triggered e-diaries allowed for new research questions and more purposeful investigation based on event-based sampling strategies since the number of assessments could be increased during periods of interest (Ebner-Priemer et al., 2012; Reichert et al., 2020). For example, participants could be asked how they felt after a long period of sitting or moving, or in visiting a green-space area (ecological momentary assessments; Giurgiu et al., 2020; Reichert et al., 2020); or they could be instructed to take the stairs, instead of the elevator, upon entering a building (ecological momentary interventions provided the moment an event of interest occurred; Heron & Smyth, 2010). Triggers for sedentary behavior (assessed by accelerometer; Giurgiu et al. 2019) and green spaces (determined by GPS-triggered geolocation information; Reichert et al., 2016; Törnros et al., 2016) are already implemented in Ambulatory Assessment studies. Herein, Giurgiu et al. (2019) investigated whether prolonged sedentary behavior is negatively associated with health outcomes, and Reichert et al. (2018) investigated whether green spaces are positively associated with health outcomes. However, the implementation of triggered instructions in Ambulatory Assessment interventions is still rare (Heron & Smyth, 2010). Since our analyses were focused on incidental physical activities in the first paper and on the differentiation of incidental physical activity, exercise, and sports in the second paper of this work, the PEZ study had some further methodological strengths. To identify the type of activity, participants were instructed to report on their incidental physical activities, exercise, and sports activities across the study week (i.e., activity duration and time points) when they returned the devices. This report was generated by a procedure that was similar to the day reconstruction method (DRM; Kahneman et al., 2004), using GPS trajectories via smartphones in combination with digital maps to enhance recall (Reichert et al., 2017; Reichert et al., 2016). This serves as one example of how research needs and technical progress facilitate and promote research in Ambulatory Assessment (details on mHealth components of the PEZ study can be seen in Fig. 1). However, for remembering the type of activity a participant performed throughout the study week, this method is already out-of-date, since accelerometers already try to automatically identify the type of activity a subject is engaged in (Farrahi et al., 2019; this issue will be discussed in more detail below, in Subject 2 of this general discussion).

Our results of the PEZ study showed that in a community-based adolescent sample, mood is an antecedent to and consequence of physical activity. Due to associations being mutually dependent, it does not always seem to be clear which variable determines the other or whether there are real effects in both directions, as we anticipated in our papers. We suggested that physical activity is both a determinant and consequence of mood (Koch et al., 2018, 2020; Reichert et al., 2016, 2017). Nevertheless, this may lead to a larger discussion of causality. To bypass the discussion of causality, micro trials would be necessary (Klasnja et al., 2015). However, with the “Pilot randomized-controlled phase IIa trial on the prevention of comorbid depression and obesity in ADHD” (PROUD) trial of the European Horizon 2020 project “Comorbid Conditions of Attention deficit/hyperactive disorders” (CoCA; CoCA, 2021; Mayer et al., 2018), we performed a preliminary step with a clinical trial investigating a mHealth intervention to prevent depression and obesity in individuals with ADHD. In addition to ecological momentary assessment (EMA, used synonymously with Ambulatory Assessment; Trull & Ebner-Priemer, 2013), which monitors and assesses data from feelings, behaviors, and situations occurring in the real world (Trull & Ebner-Priemer, 2013), as already mentioned above, it has become feasible to offer interventions via the Ambulatory Assessment method, called ecological momentary interventions (EMI; Heron & Smyth, 2010). These interventions can be delivered by smartphones, simplifying their implementation in participants’ everyday lives. The CoCA PROUD trial serves as an example for such an intervention (details on mHealth components of the CoCA PROUD trial can be seen in Fig. 1). Herein, we set up a randomized controlled trial to prevent comorbid obesity and depression in ADHD (Mayer et al., 2018).

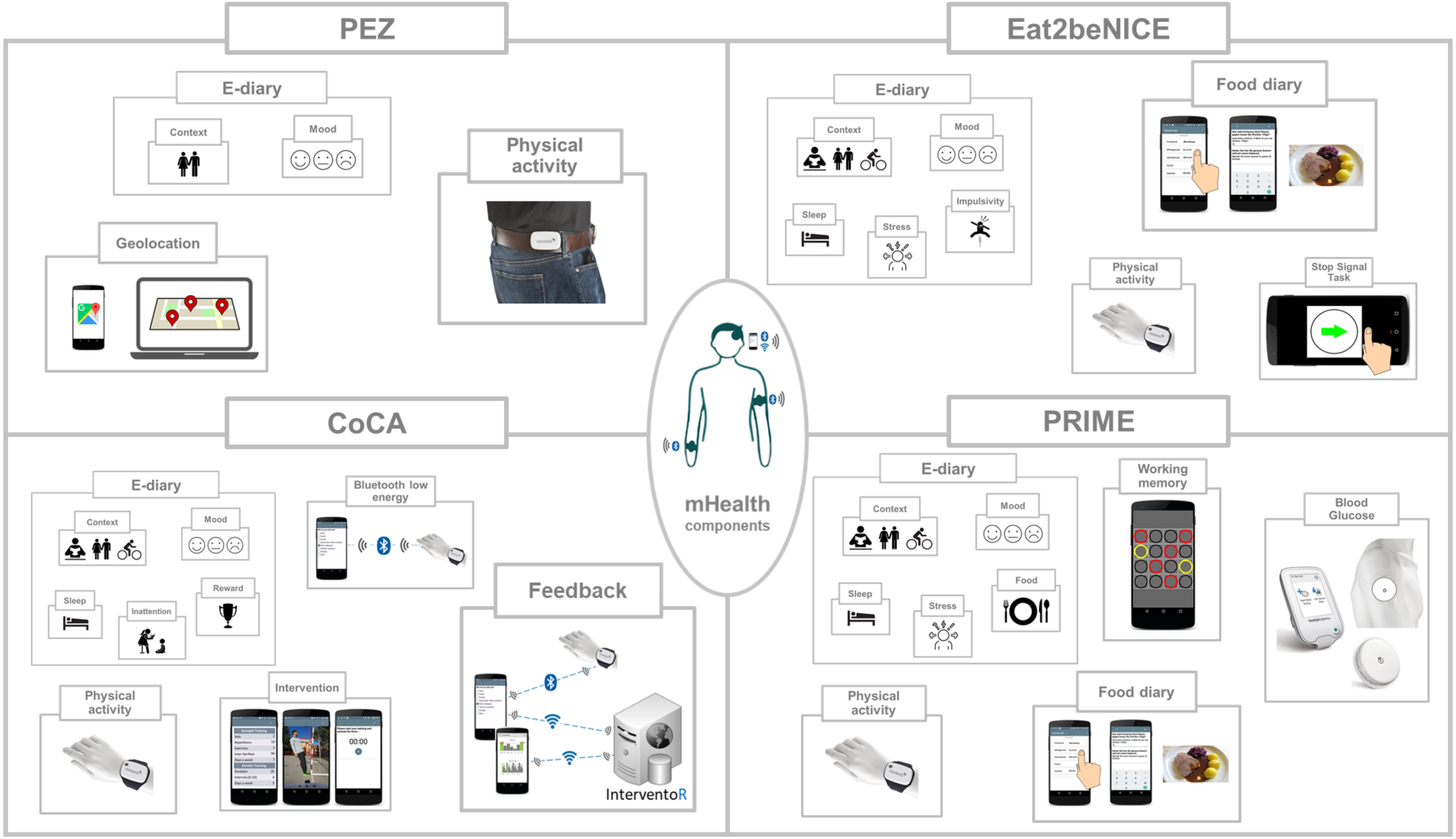

Figure 1: mHealth components of the trials of the projects PEZ, CoCA, Eat2beNICE, and PRIME (modified pictures from movisens GmbH, 2021; Pixabay GmbH, 2021)

A ten-week exercise intervention was set up via an app that showed training goals for each week (see Fig. 2); the app also sent reminders to prevent subjects from missing a training session. Additionally, the app provided a section where participants could learn the exercises performed in the strength-training program, which were prepared especially for the trial. Moreover, participants could perform their fitness exercises while watching the training videos on their smartphones. The strength-training program was prepared with three different intensity levels, offering subjects the chance to adapt the intervention to their specific fitness level. In addition, the exercises changed every week and became progressively more challenging.

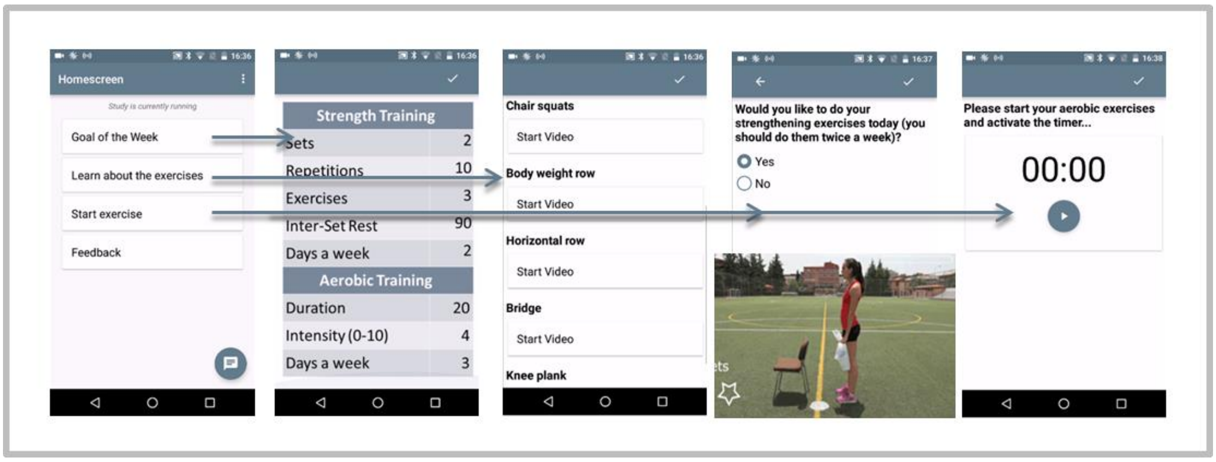

Figure 2: CoCA PROUD mHealth intervention features (modified pictures from movisens GmbH, 2021)

To investigate comorbid conditions in ADHD, the trial implemented very innovative features (e.g., automated real-time feedback) as a kind of gamification feature to motivate participants to be more compliant with the intervention. The ecological momentary intervention integrated:

a) structured and coordinated **exercise video clips** on the smartphone (refer to Fig. 1);

b) activity sensors connected to the participants' study smartphones via **Bluetooth low energy** technology (refer to Fig. 1);

c) **automated real-time feedback**, providing feedback from both the activity sensors and the smartphone (refer to Fig. 1).

Specifically, the automated real-time feedback of the mHealth approach emerged from each participant's study smartphone and the activity sensor worn on the wrist, which were connected via Bluetooth low energy technology for data transfer. Once a day in the evening, the smartphone sent data (i.e., both data from the activity sensor and data from the smartphone) to a server via a Wi-Fi connection, and the data were processed in real time to generate feedback. This feedback was sent back to the participants' smartphones approximately ten minutes later. The feedback for the exercise intervention addressed four different parameters. Feedback that was provided by the activity sensor was about the number of steps a participant took in one day and an activity curve showing movement acceleration intensity for the current day. In addition, participants received feedback assessed by the smartphone about aerobic and strengthening exercise durations that were provided in bars for the current week. Hence, daily feedback was generated automatically in real time and with the intention of improving motivation and compliance in executing the exercise interventions. The results of this trial can be taken from Mayer (2021), and the results from the baseline data of this trial are described in Chapter V. From a methodological point of view, this trial serves as a very innovative example of integrating an exercise intervention perfectly into the everyday life of participants. There was no special time and place to meet and no special equipment to use. However, along with these advantages, there were also disadvantages. In the end, this easy-to-integrate intervention turned out to be very anonymous with no obligation to make a commitment. For this reason, compliance was very low, and the interpretation of the results was challenging. Furthermore, we could address some minor technical difficulties that could arise within a multicenter trial. So-called mobile sensing (Baumeister & Montag, 2019; Kubiak & Smyth, 2019) means the collection of data using multiple sensors to monitor human behavior (Liu & Koc, 2015). This was implemented based on the data exchange between the activity sensor and the smartphone, which were connected via Bluetooth low energy technology. A Bluetooth connection requires keeping the distances of the devices to approximately less than ten meters from each other (Rashid & Yusoff, 2006). In practice, this was difficult to implement, especially because study smartphones were used instead of the participants' private smartphones (i.e., participants forgot to take the study smartphones everywhere they went). However, we used study smartphones within our trials, since they had the advantage that the smartphone and app settings could all be set equally for all the study participants. This provided the same technical requirements to all the participants within the trial and guaranteed the phone and app's appropriate and consistent functioning without major technical difficulties. Additionally, the movisensXS app was developed only for Android systems (refer to movisens GmbH, 2021), so participants with internetwork operating systems (IOSs) would not have had the chance to participate in the study. Other difficulties came up with unstable mobile networks in more rural areas. This caused problems in providing feedback to the participants due to being unable to transfer the smartphone and sensor data to the server, which was required to receive the feedback. Moreover, the market for hardware and software developments accelerates every day. It is difficult to set up trials (which are planned over the course of several years) using mHealth components, because new smartphones on the market with new features and settings, or even a simple android system update, may cause unanticipated problems in the delivery of the mHealth intervention. In addition to overcoming technical difficulties, future interventions should focus on the development of more adaptive training or other activities triggered by a subject's mood or symptoms. Additionally, automated real-time feedback should become more specific and adaptive and should reflect participants' needs and circumstances in a more individualized way. For example, by asking participants randomly several times a day about their mood or by using the GPS data to note when a movement threshold was exceeded or that a movement pattern identified someone as feeling restless, stressed, or nervous, the smartphone app could offer a training exercise to ameliorate someone's urge to move, or it could offer a relaxation exercise to ease someone's stress. In addition, feedback to increase participants' motivation and compliance with the intervention should be visually more attractive and less scientifically oriented (Mayer et al., 2018; for a visual impression of the CoCA PROUD feedback system, see Fig. 1).

Subject 2: Technical and methodological requirements for future Ambulatory Assessment research

In the second work, we focused on the definition of different categories of physical activity, since incidental physical activity, exercise, and sports showed differential effects on the mood dimensions of valence, energetic arousal, and calmness. The results show that a differentiation of physical activity categories and mood dimensions is important for obtaining a deeper understanding of these dynamic associations in real life. The results also help to clarify inconsistent findings in the literature, e.g., contrary findings or not finding any association in daily life at all (Bossmann et al., 2013; Gauvin et al., 1996; Kanning, 2012; Kanning et al., 2013, 2015; Kühnhausen et al., 2013; Schwerdtfeger et al., 2008). Hence, future investigations should consider these differentiations in their research, which may help to prepare customized physical activity interventions (referring to the PROUD trial described above).

By focusing on physical activity in research, two aspects come to mind that must be considered. First, we must find the best way to operationalize physical activity. Specifically, researchers have to consider (a) which a physical activity parameter is the best to investigate for the research question (e.g., heart rate, energy expenditure, movement acceleration, type of activity), (b) what kind of devices are suitable or required for the study planned, in order to be cost effective and less burdensome for participants (e.g., ECG, accelerometer, e-diary; Silvester et al., 2011; Trull & Ebner-Priemer, 2013), and, in relation to both of the prior points, (c) what kind of physical activity parameters can the device or software offer (i.e., output), and how reliable is the parameter as a secondary variable (e.g., energy expenditure, metabolic equivalent of task (MET) measured with accelerometers; Burchartz et al., 2020). For measuring physical activity in daily life, Ambulatory Assessment is currently the gold standard (Ebner-Priemer & Trull, 2009; Trull & Ebner-Priemer, 2013). With the Ambulatory Assessment method, we assess participants' physical activity subjectively by using smartphone questionnaires or objectively by asking participants to wear an activity sensor that measures movement acceleration intensity. The raw signal of movement acceleration intensity is the most pure and accurate parameter by which to measure physical activity with accelerometers (Burchartz et al., 2020), which was also used in the trials of the papers above (Koch et al., 2018, 2020, 2022). The signal is only high- and low-pass filtered to eliminate gravitational disturbances and artifacts other than human movements (van Someren et al., 1996). Further physical parameters offered in the output files of accelerometer analysis software are secondary variables computed from this and other raw data. Further processing of the raw signal is always accompanied by further inaccuracy due to calculation errors from respective algorithms (Burchartz et al., 2020). However, the most accurate raw signal is not always the best parameter to use, depending on the research question. For example, for measuring some very exhausting isometric exercises with one's own body weight, or for measuring weightlifting activities at all, movement acceleration intensity might indeed be insufficient. With these activities, the accelerometer may determine very low or no activity at all. Hence, movement acceleration intensity only partly represents the real intensity of human movements. Therefore, it is helpful to add parameters such as heart rate or VO_2 max measurements to show how exhausting human movements truly are (Stickland et al., 2012). One solution may be to use an ECG sensor to measure heart rate as a raw value. However, an ECG sensor only measures appropriately when a sensor with a wet or dry electrode is placed on the chest (Silvester et al., 2011), which is not always the best and most comfortable choice for participants, and even less so in longitudinal studies lasting over several weeks or even months.

The second aspect that comes to mind in the focus on physical activity, as already mentioned under Subject 1, is the assessment of the different types of physical activity that participants execute within the study period. By studying physical activity in everyday life and not in a prescribed intervention, the type of physical activity, exercise, or sports the subject engages in must be recorded in some way (refer to the PEZ study described above). Research-related accelerometers (e.g., Move3; movisens GmbH, 2021a; Anastasopoulou et al., 2014) and commercial wearables (e.g., Fitbit; Feehan et al., 2018) are still trying to automatically identify the type of physical activity by analyzing and recognizing the movement patterns and assigning an appropriate algorithm. However, algorithms to identify movement patterns are still very inaccurate. One first step to translate movement acceleration intensity into categories such as sitting, walking or running was made by Anastasopoulou et al. (2014). Another validation study from Gurgiu et al. (2020) investigated free-time living activities such as cleaning or reading a newspaper to validate body position and sedentary behavior. Furthermore, Farrahi et al. (2019) focus in their review on the need for machine learning-based approaches to calibrate and validate the type of activity captured with accelerometers. However, both the generalization capability and predictive accuracy of machine learning-based models, especially in relation to the position of the accelerometer on the body in real-life settings, still seem to be in their infancy. From a technical point of view, with some accelerometers, the signal-processing-transformation of raw data into activity counts seems to be a problem that is known to eliminate significant information needed to identify activities (Vries et al., 2011). In general, technology and algorithms have to improve to give reliable statements about the type of activity subjects engage in (i.e., activity recognition; Bassett et al., 2012; Farrahi et al., 2019; Roy et al., 2021; Wright et al., 2017). Although there is evidence that laboratory research in this field is insufficient (i.e., laboratory-calibrated models are not reproducible in free-living settings; Bastian et al., 2015), one main problem is that, due to proprietary concerns, the leading commercial producers of wearables are not sharing their algorithms and big data from the free-living activities of their customers with the research community (Wright et al., 2017). Challenges addressed here are (a) unclear data ownership; (b) the need for Institutional Review Boards to agree to the data collection practices of third parties; (c) health privacy; (d) informed consent and ethics; and (e) research methods and data quality (i.e., validity and reliability need to be proven; Bietz et al., 2016). Concerning this last point of data quality, it may be that imprecise feedback given from customers on the duration (i.e., starting and finishing time for an activity) and type of their free-living activities may lead to insufficient data quality and hence be unreliable information from which to find an appropriate algorithm. To further complicate this issue, even when customers give correct and precise feedback on the type of activity (i.e., the correct label; starting and finishing time for an activity), the reason why algorithms are still very inaccurate may be because movement patterns from different persons (between persons) may vary greatly due to specific body and movement characteristics or even due to variations in the technical and physical skills required to execute a movement (Lubans et al., 2010). This may be one additional difficulty of and reason for not finding an appropriate algorithm to generalize movement patterns that are fitting for personal people and that automatically identify the type of activity using wearables. Furthermore, it may be that movement patterns in some types of sports only differ in microspectra that need to be identified (e.g., American Football and Rugby).

To share an idea for a study design: a first step for recognizing the type of activity a person engages in could be a self-calibrating system (i.e., with machine learning processes). The self-calibrating system would have to store and recognize only the movement patterns from one person, which may be simpler and more accurate than using an algorithm generated from a pool that uses movement patterns from many different people. In detail, the idea would be to wear an activity sensor during free-living activities, exercises, or sports and to start recording the movement pattern via smartphone or via the wearable. After finishing the activity, the activity sensor or smartphone would ask for the type of activity and send the data (i.e., the activity sensor and smartphone data, as with the feedback system from the CoCA PROUD trial explained above) to a server. Artificial intelligence (i.e., machine learning processes) would be needed to store, analyze, and recognize the movement pattern, or at least parts of it (i.e., microspectra), as well as to automatically identify these movement patterns the next time the respective activity occurs. Every time the respective movement pattern comes up again, the algorithm should then recognize and label the type of activity correctly and ask the participant for verification (refer to Fig. 3). In the sense of machine learning processes, the algorithm would be more appropriate with more verified and correctly labeled data. Since a movement pattern from one person (within person) should be the same, or at least very similar, every/over time, which may overcome the difficulty of generalizing different movement patterns across persons (between persons) to find one appropriate algorithm that is suitable for everyone. For a research trial focusing on the type of activity, this would be an idea for a study design that may lead to more valid and reliable data for every person individually. However, by measuring longer periods (i.e., over weeks or months), one further difficulty might be that movement patterns may also change within a person from the very beginning of learning a movement technique to truly knowing how to execute it at a higher level (i.e., advanced physical and technical skills; Lubans et al., 2010; Pink, 2008). To overcome this limitation, the calibration process would need to be refreshed as soon as the algorithm worsens and can no longer automatically identify the type of activity.

In general, technology and algorithms must improve their ability to clearly identify microspectra within the movement patterns of free-living activities, exercises, or sports that are shown only in the respective type of activity (e.g., there may be microspectra typical to American Football that are not common in Rugby). In the future, for any one type of activity, these microspectra may also reflect persons with different body and movement characteristics as well as different physical and technical skill levels and thus automatically and precisely identify the type of activity.

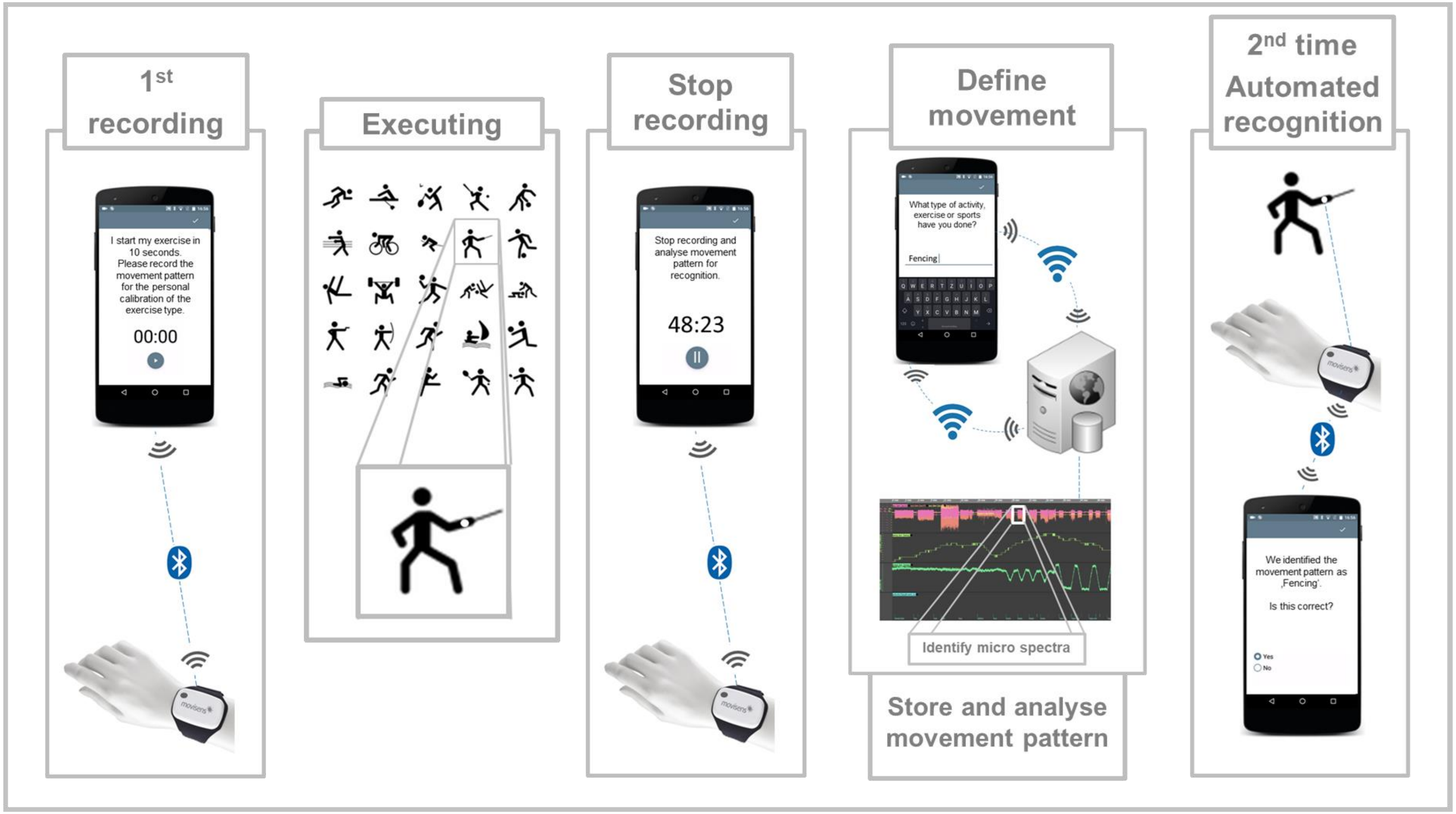

Figure 3: Idea for the implementation of a self-calibration process to recognize the type of activity within a person using a smartphone, accelerometer and server (modified pictures from movisens GmbH, 2021; Pixabay GmbH, 2021)

Subject 3: Ambulatory Assessment to support psychiatric practices and to improve diagnoses in a clinical context

Using technology such as smartphone apps to monitor a patient's symptomatology moment-by-moment, on a within-person level, in his or her own environment and with the intention of providing an even more precise diagnosis of a disorder, is called digital phenotyping (Barnett et al., 2018; Onnela & Rauch, 2016; Rajagopalan et al., 2017). The similarity of symptoms, side effects and comorbidities, especially among mood disorders, makes their diagnosis using biological markers challenging. Biomarkers are found to be insufficient indicators on which to base precise diagnoses, and cross-sectional evaluations are gaining in importance (Brietzke et al., 2019). By combining diagnostic methods, it is possible to overcome methodological weaknesses or false diagnosis (Brietzke et al., 2019).

Another chance to support diagnosis in clinical settings seems to be cognitive tasking via smartphones. To date, there exist many validated tasks for measuring cognitive functions objectively using a computer interface (e.g., stop signal task (SST), working memory, balloon, or morphing task; Bland et al., 2016; Verbruggen & Logan, 2008) but rarely are these used on smartphones (Jones et al., 2018; Smittenaar et al., 2015). The validation of these same tasks on smartphones is of special importance since the innovative and objective Ambulatory Assessment instrument offers the opportunity to measure subjects' cognitive functioning in the everyday life. With this, researchers can investigate associations between fluctuating physical and cognitive parameters over time. One of the tasks mentioned above is the SST, which measures impulsivity based on impulse control (i.e., response inhibition). Specifically, higher impulsivity is associated with poorer response inhibition (Verbruggen & Logan, 2008). We implemented the stop signal task in Ambulatory Assessment studies by using the movisensXS app (for more information refer to movisens GmbH, 2021b) to launch the neurobs presentation app (for more information refer to Neurobehavioral Systems, 2021), which opens by filling out an e-diary request. The task shows green arrows, either to the right or to the left side of the smartphone screen in landscape mode. The participants are instructed to touch the screen either on the right or the left side, as shown by the green arrow, and as fast as possible, but also to avoid making mistakes. In some cases, the green arrow turns to a red color. The participants were then instructed to inhibit the response and not to touch the screen when the arrow turned red. The fewer mistakes the participants made in avoiding touching the screen when the red arrow appeared, the better the impulse control. Especially in individuals with ADHD, the SST activity was a good opportunity to measure impulsivity objectively as one of the main symptoms of the disorder (Alderson et al., 2007). In combination with accelerometers and food diaries, the investigation of associations between nutrition (e.g., sugar) and impulsivity or how physical activity may influence impulsivity in daily life becomes feasible. Such an investigation was implemented in the APPetite trial of the European Horizon 2020 "Effects of Nutrition and Lifestyle on Impulsive, Compulsive, and Externalizing behaviors" (Eat2beNICE) study, which evaluated the preventive or protective effects of physical activity and dietary patterns on impulsive behaviors in population-based and patient samples (for more information, refer to Eat2BeNice, 2020; for details on mHealth components of the Eat2beNICE APPetite trial, see Fig. 1). Another EU study, "Prevention and Remediation of Insulin Multimorbidity in Europe" (PRIME), investigated insulin-dependent mechanisms in type 2 diabetes (for more information, refer to PRIME, 2021; for details on mHealth components of the PRIME project, see Fig. 1). In that trial, (1) a glucose sensor was worn on the arm, (2) an accelerometer was worn on the wrist, and (3) an e-diary on a smartphone with integrated food diary and additional cognitive tasking gathered data to show associations between glucose levels, physical activity, eating behavior, and working memory. Specifically, the FreeStyle Libre Pro Flash Glucose Monitoring System (for more information refer to Abbott, 2021) on the arm measured glucose levels every 15 minutes. The data were sent to a reader and could be read out by the related software on the computer after the measurement was taken. Furthermore, the working memory task could be focused either on a spatial n-back task (used more often in children; Cohen et al., 1997; Schmiedek et al., 2010) or a numerical memory-updating task (used more often in adults; Riediger et al., 2014; Salthouse et al., 1991; Shing et al., 2012). The numerical memory-updating task, which was used in PRIME, is a computational task in which participants are instructed to update operations (i.e., additions and subtractions). More specifically, at the beginning, three numbers are presented in a row on the smartphone screen, which each displayed for several seconds. The participants were instructed to keep the numbers in mind. Then the numbers disappeared, and a single number appeared in one of the cells where a number previously had been presented. This new number should be added or subtracted from the earlier number that was presented in that particular cell (i.e., updating operation). After several rounds with changing presentation of numbers in different cells, the result should be entered for each of the three cells. The better the result in the end (i.e., one, two or three numbers correct) are, the better the working memory.

The mHealth system of the PRIME study combines several devices and tools to give a holistic picture of the interplay between physical and mental states and whether or how they are mutually associated over time. The mentioned requirements are currently executed retrospectively in formatting and merging several datasets from different devices and with different outputs. Future studies should focus on the need to enhance hardware and software approaches, to combine the required features to minimize the burden on participants, and to facilitate data analysis for researchers. A first step toward minimizing the burden on participants is to trigger and integrate several measurements into one application (e.g., to trigger the neurob presentation app using the movisensXS app, as explained earlier). In a second step, an automatically generated output providing a dataset with data from every device would greatly simplify data analysis in the PRIME project.

Measuring food intake in daily life is still very challenging in research (for an overview, refer to Foster & Adamson, 2014). Nevertheless, as mentioned above, we implemented a food diary within the trials of the EU projects Eat2beNICE and PRIME. In these trials, participants were asked to document every meal, snack, and drink they took within a day. The focus was on what kind of food people ate, what amount, how many portions, and what ingredients were in these foods. By not being able to scan a barcode from the packaging or to weigh the exact portion of every component, we were not able to know the exact amount of sugar, fat or vitamins people consumed, even though we are able to link the food to a food and nutrition database for dietary studies (Six et al., 2011). To date, there are several apps that may help to measure food intake very accurately by (1) scanning the barcode of the respective food and weighing it exactly (e.g., Fddb extender; Kaiser et al., 2020); (2) making use of a food drop-down menu with an additional search option to find the correct menu option (Ruf et al., 2021); and (3) taking a photo of the plate (e.g., SACANA, Hebestreit et al., 2019), before and after having finished the meal – there may be some food left on the plate. However, when study participants went out for a meal, e.g., in a restaurant or canteen, we could not see or know the exact amount of oil or butter the respective food was prepared with. Furthermore, for the third option, there always must be a calibration object in the photo to enable the assessment of the exact size of the plate and portion. This is also challenging since we would, ideally, have to take a three-dimensional photo instead of a two-dimensional photo to have the x, y, and z axes. Hence, artificial intelligence is needed that can exactly recognize the type of food and the exact portion size. This is partly already feasible with tools such as myfood24 (Wark et al., 2018) or SACANA (Hebestreit et al., 2019), but this technology is still in its infancy.

Subject 4: Movement patterns as digital markers of symptomatology in mental disorders

The fourth paper of this work is part of the CoCA project, partly described above (Mayer et al., 2018). In this study, only baseline data from the preintervention assessment of the CoCA PROUD trial were used. To further discuss the results that showed that physical activity increased positive affect, especially among individuals with the combined presentation of

ADHD symptoms (i.e., inattention and hyperactivity), and that showed that physical activity only decreased negative affect in this subgroup, we speculate the following. How could we attempt to explain the mechanism by which physical activity is beneficial in improving mood, especially among individuals who are more hyperactive than those in the other subsamples? One explanation could be that reinforced behavior will occur more often due to operant conditioning laws. Specifically, when applied to the mood-enhancing effect of physical activity, individuals with a more pronounced mood-enhancing response to physical activity will perform physical activity more often. As the ADHD group with a combined presentation of symptoms showed the most intense increases in positive mood and this group was the only with decreases in negative mood, negative reinforcement law would predict that physical activity will occur more often, especially in this group. However, further studies are needed to investigate whether the mood-enhancing effect in combination with operant conditioning may be an explanation for hyperactivity, at least partially.

Movement patterns, which are typically hyperactive (i.e., fidgeting) for individuals with ADHD, are hard to identify with accelerometers (Muñoz-Organero et al., 2018). In our study, assessing physical activity with accelerometers, we did not find individuals with the combined presentation of symptoms (i.e., individuals being more hyperactive) to be more physically active (i.e., to have a higher mean movement acceleration intensity; mean: 95,9 millig; sd = 31.32) than are individuals with a predominantly inattentive presentation (mean: 97,5 millig; sd = 23.04). One reason could be that we included adolescents and adults in our study, who are known to lose hyperactivity as they progress through developmental stages and who are, hence, less hyperactive than children (Asherson, 2012). Moreover, adults are well known to have obligations throughout the day (i.e., working), which limits opportunities to act out their urge to move. Nevertheless, in identifying types of activity, and referring to the self-calibrating subject from earlier, future studies should investigate movement patterns that are typical of individuals with ADHD, and these patterns should be compared to control participants. Muñoz-Organero et al. (2018) performed a first step in comparing movement patterns from children with ADHD and controls and found the majority of acceleration patterns to be equal. With spectral analyses of movement patterns, we should be able to identify micro differences in the movement spectra of individuals with ADHD and controls. By identifying an unmistakable marker for diagnosing hyperactivity in acceleration patterns, this could result in an additional diagnostic tool to support clinicians in diagnosing ADHD via digital phenotyping.

Generally, mental disorders and mood dimensions are closely related to each other. Healing a mental disorder is a very challenging undertaking, but research aims to improve the main and co-occurring symptoms and hence to improve quality of life. This target can be reached by understanding the underlying mechanisms and related components of a disorder to better alleviate symptoms, comorbidities, and side effects. With technical progress, digital phenotyping becomes feasible, simplifying the diagnosis of patients by implementing close monitoring of the respective physical parameters of the patients' symptoms, feelings and behaviors in their daily lives, which was not possible in in the past. By identifying key parameters shown to improve co-occurring effects of a disorder, chances are high that one improves the associated main symptoms of the mental disorder as well (e.g., improving negative affect may improve impulsivity in ADHD as well). Past and current studies have shown physical activity to be a key parameter, potentially improving mood in community-based and clinical samples. In healthy individuals, this may prevent the appearance of mental disorders, and in patients with a mental disorder, this may improve symptoms or the outcome of the disorder. Future technological progress will foster the identification of phenotypes using digital tools to help establish interventions and therapies, thus addressing the specific needs of patients even more individually and effectively.

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