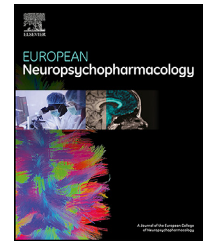
European Neuropsychopharmacology 57 (2022) 69–74



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SHORT COMMUNICATION

The dynamical association between physical activity and affect in the daily life of individuals with ADHD

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https://doi.org/10.1016/j.euroneuro.2022.01.110

Received 23 November 2021; received in revised form 20 January 2022; accepted 24 January 2022

KEYWORDS
ADHD;
Ambulatory Assessment;
Physical activity;
Affect;
Mood

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.

1. 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 and 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). 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 (Gawrilow et al., 2016; Emmerson 2010). 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 and 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 and Ebner-Priemer 2013). The AA method assesses both between-subject and within-subject effects, depicting fluctuations over time (Trull and Ebner-Priemer 2013; Kanning et al., 2015). 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 (Ebner-Priemer et al., 2012; Adamo et al., 2009).

Hence, we investigated the within-subject associations between physical activity and positive / negative affect in adolescents and adults with ADHD. Based on the findings reported above, we hypothesized a positive association between physical activity and positive affect and a negative association between physical activity and negative affect. Additionally, we expected steeper slopes in positive and negative affect in the individuals with ADHD compared to controls.

2. Experimental procedures

Within the framework of the European trial 'CoCA PROUD' (a trial to prevent comorbid depression and obesity in ADHD; further details on patient characteristics and enrollment can be found in Mayer et al., 2018) we investigated individuals with ADHD and control participants between 14 and 45 years of age in four European clinical sites at Frankfurt, Nijmegen, London, and Barcelona. Herein, we received e-diary and acceleration baseline data (i.e. data before starting the intervention) from 236 participants ($n = 183$ individuals with ADHD and $n = 53$ controls) out of the 207 individuals with ADHD who were randomized to the intervention afterwards. 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. Included 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). Exploratively, we divided the sample of individuals with ADHD according to their predominant symptoms (i.e., predominantly inattentive presentation, predominantly hyperactive presentation, and a combined presentation of being both inattentive and hyperactive), based on the proposal that the predominant symptoms could be understood as distinct disorders (Milich et al., 2001). Classification of the predominant ADHD symptoms was established by the respective structured clinical interview (K-SADS-PL for adolescents, Kaufman et al., 1997; DIVA 2.0 for adults, Ramos-Quiroga et al., 2019). As no patient was classified as "predominantly hyperactive", we ended up with the two subsamples "predominantly inattentive presentation" and "combined presentation". 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). Controls were only recruited in Frankfurt and London. Participants' physical activity was measured 24 h per day, for four days, objectively with an acceleration sensor on the non-dominant wrist (LightMove 3, movisens GmbH), with a measurement range of ±8 g and a sampling frequency of 64 Hz. Raw-acceleration data were analyzed by the software DataAnalyzer (movisens GmbH, version 1.6.12129) to compute the movement acceleration intensity per minute [millig/min]. For the same four days, a smartphone app (movisensXS; movisens GmbH) provided twelve random e-diary prompts per day (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; Myin-Germeys et al., 2003). 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 (Kanning et al., 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.

3. Results

The two patient groups did not differ regarding gender, age, BMI and comorbid depression scores (shown in Table 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 Table 1).

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 Table 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

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)	

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/m²]	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/m²]	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

presentation ($p = 0.025$) and controls ($p = 0.002$; shown in Figure 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.

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 and 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 Figure 1b).

4. Discussion

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

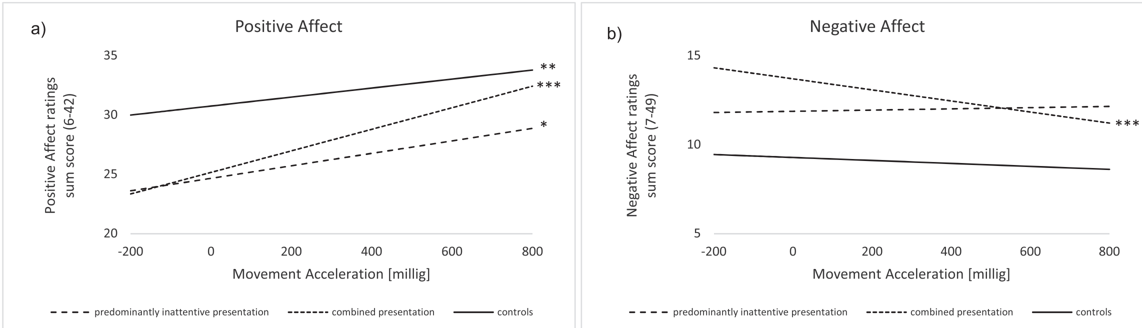

Fig. 1 a. Positive affect and b. negative affect slopes in the ten minutes after low, average and high levels of physical activity on a person's mean score. Positive and negative affect were measured by 7-point Likert scales (positive affect range: 6–42; negative affect range: 7–49; y-axis) depending 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 $^{*}P \leq 0.05$, $^{**}P \leq 0.01$, and $^{***}P \leq 0.001$.

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). 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). 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).

To conclude, we prospectively investigated, how physical activity and affect fluctuate 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 affect. 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.

Author disclosure

Role of Funding Source. This study was supported by the EU Framework Program for Research and Innovation, Horizon 2020 (Project no. 667302, "CoCA" – funding period: January 2016–December 2020) and the ECNP Network ("Digital Health Applied to the Clinical Research of Brain Disorders").

Statement of Ethics. The local ethics committees of the four clinical sites as follows approved the study: Goethe University Frankfurt, Germany; Radboud University Medical Center Nijmegen, Netherlands; King's College London, United Kingdom; and Vall d'Hebron Research Institute Barcelona, Spain. They followed the ethical guidelines for medical research (i.e., the Declaration of Helsinki). All participants (and the parents of underage participants) were informed about procedures and data protection in the study before signing informed consent forms. The participants had the possibility to withdraw from the study at any time without any consequences.

Author contributions

All co-authors have revised the manuscript and approved this submission.

Conflict of Interest

In the past 3 years, Jan K Buitelaar has been a consultant to/member of the advisory board of/and/or a speaker for Takeda/Shire, Roche, Medice, Angelini, Janssen, and Servier. He is not an employee of any of these companies and is not a stock shareholder of any of these companies. He has no other financial or material support, including expert testimony, patents, and royalties.

Ulrich W. Ebner-Priemer has received consultant fees from Boehringer Ingelheim.

Acknowledgments

We thank Clara Hausmann for her assistance in data management and preparing the dataset.

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