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CLINICAL REVIEW

The use of actigraphy in the monitoring of sleep and activity in ADHD: A meta-analysis

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SUMMARY

Attention deficit/hyperactivity disorder (ADHD) is the most common neurobehavioral disorder of childhood. There is an increasing need to find objective measures and markers of the disorder in order to assess the efficacy of the therapies and to improve follow-up strategies. Actigraphy is an objective method for recording motor activity and sleep parameters that has been used in many studies in ADHD.

Our meta-analysis aimed to assess the current evidence on the role of actigraphy in both the detection of changes in motor activity and in sleep patterns in ADHD.

A systematic review was carried out to find studies comparing children with unmedicated ADHD versus controls, using actigraphic measures as an outcome. The primary outcome measures were "sleep duration" and daytime "activity mean". As secondary outcome measures we analyzed "sleep onset latency", "sleep efficiency" and "wake after sleep onset".

Twenty-four studies comprising 2179 children were included in this review. We show evidence that ADHD compared to typically developing children present a higher mean activity during structured sessions, a similar sleep duration, and a moderately altered sleep pattern.

This study highlights the role of actigraphy as an objective tool for the ambulatory monitoring of sleep and activity in ADHD.

Introduction

Attention deficit and hyperactivity disorder (ADHD) is among the most prevalent childhood psychiatric disorders, with an estimated prevalence rate of 5% [1]. The scientific community agrees that ADHD is a complex and multifactorial disorder and that it is not the result of one clear or single cause. The most frequently cited aetiological hypotheses are genetic, neurochemical, neurobiological, and environmental [2].

According to the diagnostic and statistical manual of mental disorders, fifth edition (DSM-5) [3], ADHD is characterized by a persistent pattern of inattention and/or hyperactivity-impulsivity that interferes with functioning or development with onset before the age of 12 y. More specifically, the DSM-5 diagnosis of ADHD requires six symptoms of hyperactivity and impulsivity or six symptoms of inattention, while for older adolescents and adults (age 17 and older), at least five symptoms are required. Manifestations of ADHD must be present in more than one setting (e.g., home and school, work) and persist for at least six months [3]. The DSM-5 defines three ADHD clinical presentations based on symptom count: combined presentation, predominantly inattentive presentation and predominantly hyperactive/impulsive presentation. The ICD-10 [4] uses the specific diagnostic term of hyperkinetic disorder (HKD) to describe the

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Glossary of terms

ADDES-H	attention-deficit disorders evaluation scale – home version
ADDES-S	attention-deficit disorders evaluation scale – school version
ADHD	attention-deficit/hyperactivity-disorder
ADHDRS	attention-deficit/hyperactivity-disorder rating scale
APA	American psychiatric association
CBCL	child behavior checklist
CI	confidence interval
CGI-S	clinical global impression – severity of illness
CPRS	Conner's parent rating scale
CPT	continuous performance test
CSHQ	children's sleep habits questionnaire
CSI	child symptom inventory-parent and teacher
CSP-Q	child sleep questionnaire – parent version
CTQ	Conner's teacher questionnaire
CTRS	Conner's teacher rating scale
DISC IV	diagnostic interview schedule for children
DSM-5	diagnostic and statistical manual of mental disorders 5th edition
ESS	Epworth sleepiness scale
FBB-HKS	questionnaire for teacher – hyperkinetic syndrome
HKD	hyperkinetic disorder
ICD-10	international classification of diseases 10th Edition
ISI-C	insomnia severity index for children
K-ARS	ADHD rating scale, korean edition
K-DIPS	diagnostisches interview fur psychische storungen im kindesalter
K-SADS-PL	kiddie-sads-present and lifetime version
MFFT	matching familiar figure test
MPH	methylphenidate
MSLT	multiple sleep latency test
NEPSY	developmental neuropsychological assessment
NES	neurobehavioral evaluation
N.R.	not reported
PACS	parental account of childhood symptoms
PIAT	Peabody individual achievement test-revised
PICS	parent interview for child symptoms
PPVT-R	Peabody picture vocabulary test revised
PSG	polysomnography
P-YRMS	parent version of the young mania rating scale
RCPM	Raven's colored progressive matrices
SLAQ	sleep lab adaptation questionnaire
QUADAS	quality assessment of diagnostic accuracy studies
SMD	standardized mean differences
SD	standard deviation
SSD	stop signal delays
SWAN-F	symptoms and normal behavior questionnaire
TBI	traumatic brain injury
TD	typically developing
TRF	teacher report form
TTI	teacher telephone interview
WAIS-III	Weschler adult intelligence scale 3rd edition
WHO	world health organization
WISC-III	Weschler intelligence scale for children third edition
WISC IV	Weschler intelligence scale for children fourth edition
WPPSI	Weschler primary and preschool intelligence test
WRAT-R	wide range achievement test revised

syndrome, which comes close to meeting the criteria for the combined clinical presentation of DSM-5. Specifically, HKD requires symptoms of impaired attention, hyperactivity and impulsivity in more than one setting (e.g., academic, social, and occupational).

The current clinical understanding of ADHD does not require performance of any screen or test [5] and the assessment includes both a medical and a psychological clinical evaluation based on DSM-5 [3] or ICD-10 [4] criteria. The clinical evaluation of ADHD is multidimensional to capture its situational variability, its associated features, and its impact on home, school, and social functioning. The multi-method assessment approach should include: general medical history; DSM-5 or ICD-10 based parent and child interviews (e.g., Kiddie schedule for affective disorders and schizophrenia for school-age children—present and lifetime, K-SADS-PL [6]); parent- and teacher-completed child behavior rating scales (e.g., Conners third edition [7]); individually administered neuropsychological and intelligence testing (e.g., Wechsler intelligence scale for children –fourth edition [8]); educational achievement testing and screening for learning disabilities; assessment for coexisting psychiatric disorders including oppositional defiant disorder, conduct disorder, mood disorder, anxiety disorder, obsessive compulsive disorder, abuse; general assessment for coexisting medical conditions; educational and psychosocial evaluation. Other assessments might be warranted for further evaluations including: blood lead level, thyroid hormones, genetics consultation/testing, neurology consultation/electroencephalography [9,10]. At present, the diagnosis is based on subjective measures and there is an increasing need to find objective measures and markers that overcome the existing differences in definitions and that help to monitor the clinical evolution of individuals with ADHD.

Treatment of ADHD may involve behavioral interventions, school-based interventions, psychological interventions or medication (psychostimulants) alone or in combination. Psychostimulants, such as methylphenidate (MPH), amphetamines and/or various amphetamine and dextro-amphetamine preparations are the most common types of medication that have been shown to be effective for treating ADHD. The treatment strategies for children with ADHD vary according to age [9]. Behavioral interventions include modifications in the physical and social environment that are designed to change behavior using rewards, positive reinforcement, and non-punitive consequences [9,11]. Behavioral interventions are preferred to medication as the initial intervention for preschool children with ADHD but medications may be used as an adjunct to behavioral interventions for preschool children (four through five y) who fail to respond to behavioral interventions alone. Combination therapy uses both behavioral/psychological interventions and medication. In a systematic review and a meta-analysis, combination therapy was more effective than behavior/psychological therapy alone in improving core symptoms of ADHD but no more effective than medication treatment alone [12,13]. Parenting programs give parents simple and practical strategies to help them manage their children's behavior, and prevent problems. School-based interventions may include the provision of tutoring or resource room support, classroom modifications, accommodations, or behavioral interventions [9].

If left untreated, ADHD is associated with long-term educational and social disadvantage [14]. Indeed, children affected by ADHD are at greater risk for comorbid antisocial behavior, poor academic or vocational performance, substance misuse, and other psychiatric disorders such as anxiety and depression [15]. Moreover in ADHD there is a higher incidence of sleep onset insomnia [10], night awakenings, delayed sleep phase and increased nocturnal activity [16,17] and ADHD symptoms often overlap with those observed in children suffering from sleep deprivation [18]. However, studies examining the association between ADHD or its symptoms and sleep disturbances have yielded inconsistent results [19]. Using subjective (e.g., questionnaires) and objective (neurophysiological) measures, several studies have attempted to clarify the links between ADHD and sleep disorders. Studies using subjective measures (e.g., sleep questionnaires completed by parents) found that children with ADHD have more sleep disturbances compared with typically developing (TD) children, while studies using objective measures (e.g., polysomnography [PSG] and actigraphy) lead to inconsistent results [20]. The heterogeneity of results might be due to the use of medication and the night-to-night variability of sleep [21].

Actigraphy is a non-invasive objective method for recording motor activity and sleep parameters by means of an electronic device worn on the body. The main motor activity parameter assessed by actigraphy is the “activity mean”. Sleep parameters are derived from night-time activity scores. The main sleep parameters are “sleep duration”, which is the sleep time excluding all periods of wakefulness; “sleep onset latency”, which is the time in minutes from getting into bed to actigraphically defined sleep onset (this usually happens after the first 10 min interval of activity below the threshold set for determining wakefulness); “sleep efficiency”, which is the ratio of total sleep time, to nocturnal time in bed; “wake after sleep onset”, which is the period of wakefulness after sleep onset. The actigraph allows a patient's activity information to be obtained either in an experimental setting or in a natural setting for a prolonged and continuous period. In recent years, actigraphy has become a major assessment tool, especially in sleep research, sleep medicine, and proved to be reliable [22], valid [23], and cost-effective [24]. In a previous meta-analysis of randomized clinical trials we already evaluated the use of actigraphy as a measure of monitoring activity mean and sleep patterns in children with ADHD treated by MPH [25]. Our results suggested that actigraphy might be a valuable tool for prescribing clinicians who must balance the efficacious effects on hyperactivity against the adverse effects on sleep that MPH may have. However, we recognized that these initial results needed a measure of comparison, since the data comparing actigraphic measures in ADHD versus healthy controls had never been pooled. This implied that we did not have a reliable estimate of the difference between a child with ADHD and a TD child.

The present study therefore is aimed at systematically reviewing and quantitatively synthesizing the current evidence on the role of actigraphy in the detection of changes in activity and sleep patterns in ADHD compared with TD children. Our hypothesis is that actigraphy is a valid measure of the mean activity level and a tool for monitoring its impact on sleep patterns, which could contribute to the clinical diagnosis of ADHD.

Methods

Literature search

A literature search of the PubMed/MEDLINE, CINAHL, ISI web of knowledge, Cochrane library, Psychology and behavioral sciences collection databases was carried out to find relevant peer reviewed articles comparing actigraphic measures in children with ADHD versus TD children. A search algorithm based on a combination of the terms: (ADHD OR attention deficit OR ‘hyperactivity disorder’) AND (actigrap* OR actimet* OR actograp* OR actomet* OR accelerometer) was used. No lower date limit was used and the search was continued until July 2014. To expand our search, reference lists of the retrieved articles were also screened for additional studies (the search strategy is available in the supplementary material as document S1).

Study selection

All studies or subsets of studies in children with ADHD having an actigraphic assessment for both sleep and activity were eligible for inclusion.

The exclusion criteria were: a) articles not within the field of interest of this review; b) review articles, editorials or letters, comments, conference proceedings; c) case reports; d) studies dated before 1990 if the system used for the diagnosis did not use operationalized criteria, but only disease names with no diagnostic criteria (i.e., ICD-9); e) studies with patients aged more than 18 y; f) studies in children with ADHD on a pharmacological treatment; g) studies without a control group of TD children; h) studies without a proper diagnosis of ADHD; i) studies on children with ADHD and a serious concomitant medical illness.

Two researchers (SL and MC) independently reviewed the titles and the abstracts of the retrieved articles, applying the inclusion and exclusion criteria mentioned above. The same two researchers then independently reviewed the full-text version of the articles to confirm their eligibility for inclusion. Disagreements were resolved in a consensus meeting or by a third reviewer (FDC). Considerable care was taken to exclude duplicate publications.

Data extraction

For each included study, information was collected systematically and independently by the two researchers mentioned above about the publication (author names, journal, year of publication, country of origin), the patient and the comparison characteristics (gender, age, how the diagnosis was made, the outcomes of the study, actigraphic methodological features). Data were then extracted independently and entered into RevMan 5.3 software by two review authors (MC, FDC).

Outcome measures

The primary outcome measures were the analyses of “sleep duration” and of “activity mean”. As secondary outcomes, we analysed “sleep latency”, “sleep efficiency” and “wake after sleep onset”, which are considered less reliable parameters for actigraphy [22].

Quality assessment

The methodological quality and potential sources of bias for each study were assessed by using the quality assessment of diagnostic accuracy studies (QUADAS) [26]. This instrument consists of eleven items. The first of them assesses the representative spectrum; the second, fourth, fifth and sixth item examine the applicability of an appropriate reference standard; the third item assesses the presence of a delay between the tests; the seventh and eighth items assess the blinding; the ninth indicates whether relevant clinical information was available

during the interpretation of results; the tenth item examines whether all the results were reported; while the eleventh item assesses whether all the withdrawals from the study were explained. Two authors scored independently (SL, MC), and differences were resolved by consensus or by a third reviewer (FDC). Moreover, funnel plots were visually checked to exclude the presence of publication bias.

Data analysis

Consistent with meta-analytic recommendations [27], we synthesized and analysed our set of studies. This procedure involved the following steps: a) calculating standardized mean difference (SMD) effect sizes for each comparison with confidence intervals (95%); b) determining an overall effect size; c) estimating heterogeneity.

Data for each study were expressed as standardized mean difference, since differences on actigraphic devices and on storage rates used suggested we should think of them as different measurement scales, using the random effects model which is more conservative than the fixed-effects model. To check for the existence of publication bias, visual inspection of the data was completed using funnel plots, and any potential outliers were identified within each domain. Qualitative data have been presented descriptively.

The I^2 index was used to assess the heterogeneity of effect sizes [28]. Its value lies between 0 and 100 and estimates the percentage of variation among effect sizes that can be attributed to heterogeneity. A significant I^2 suggests that the effect sizes analysed are not estimating the effect size of the same population. Following Higgins et al. [28], we discussed I^2 thresholds of 25%, 50% and 75% to differentiate low, moderate and high heterogeneity. In interpreting SMD values, we considered SMD "small" if < 0.40, "moderate" from 0.40 to 0.70 and "large" if >0.7 [27]. In order to address heterogeneity, to estimate outliers and to examine the robustness of the results, we performed a sensitivity analysis using the jackknife method for the primary outcomes [29].

Moreover, we decided to perform a separate sensitivity analysis on the activity mean during the 24 h and during structured experimental sessions.

Results

Selected studies

The literature search generated 354 articles. Reviewing titles and abstracts, articles were excluded applying the criteria mentioned above: 268 studies were excluded because they were not within the field of interest of this review and 86 articles were retrieved in full text. Of these, 25 studies were excluded because some of the participants or all of them were on pharmacological treatment; 16 studies were excluded due to lack of TD control population or no control population at all; three were letters to the editor; 12 were studies with a population without a proper ADHD diagnosis; four studies were with subjects older than 18 y; one study was with children with developmental coordination disorder and comorbid ADHD and one study was not on humans (references of the excluded studies are available in the supplementary material as document S2).

Finally, 24 studies comprising 2179 participants were included in a qualitative synthesis [17,19,30–51]. Of these 19 studies (eight assessing activity mean and eleven studies assessing sleep parameters) comprising a total of 1323 children (631 ADHD and 692 TD) were included in the quantitative analysis (see flow chart as Fig. 1).

Study characteristics

The characteristics of the included studies are presented in Table 1. Almost all the studies retrieved were in English, but one was in German [47]. The majority of participants were male, with a mean age of nine years, one study included children between three and four years [30] and one study included adolescents with a mean age of 15.1 y for ADHD and 14.1 y for controls [38].

The methodological aspects of actigraphic devices are presented in Table 2. Actigraphic devices varied and the specific types of device were not always reported. Actigraphic devices were worn in most studies on the non-dominant wrist, but some reported their use on the ankles or on the waist. The storage rate used was not always reported, but for the most, it was around 1 min epoch. When the actigraph was used to detect activity mean, the device was continuously used during 24 h only in two studies [39,42], while for the rest of the studies it was on average used only for a couple of hours during experimental sessions.

Primary outcomes

Effect sizes with 95% confidence intervals for each parameter from each individual study plus the pooled results from the meta-analyses are shown in Tables 3–7. The primary outcomes are shown in Tables 3 and 4. The meta-analysis indicates that children with ADHD have a moderately increased activity mean compared to TD (SMD = 0.65 [0.45, 0.84], P < 0.00001). There is homogeneity among the studies (I^2 = 19%) and the jackknife analysis (see Table S3) confirms the robustness of this result. The sensitivity analysis dividing the results of the activity mean during the 24 h and during structured experimental sessions highlights that only two small studies reported an activity mean during the 24 h [39,42] and the pooled meta-analysis does not show a statistical difference between ADHD and TD children. However reaching statistically significant results would have been difficult due to the size of the studies (28 ADHD compared to 28 TD children), which resulted in a wide confidence interval (SMD = 0.24 [−0.29, 0.77]). We found instead that results are highly suggestive towards the use of actigraphy during structured experimental sessions, with a strong increase of activity mean and a clear homogeneity among the studies (SMD = 0.71 [0.51, 0.90]); I^2 = 15%).

Notably, we had to exclude Rapport et al. (2009) [41] from the analyses, since it presented results as a sum of three actigraphic devices. Its results highlight a much higher activity mean in ADHD compared with TD children (SMD = 2.43 [1.31, 3.56]).

The meta-analysis of sleep duration is not significant and indicates that there is no evidence that children with ADHD compared to TD have different sleep duration. There is homogeneity among the studies (I^2 = 7%), while the jackknife analysis (see Table S4) suggests a possible small reduction in sleep duration for ADHD children.

Secondary outcomes

The secondary outcomes are shown in Tables 5–7 The meta-analysis of sleep latency shows a significant and moderate increase in ADHD compared to TD children (SMD = 0.51 [0.10, 0.92]). The high heterogeneity (I^2 = 79%) creates a larger confidence interval in the random effects model, but the estimate remains significant (P = 0.01). The sleep efficiency parameter also indicates a moderate effect with a lower score in ADHD (SMD = −0.69 [−1.32, −0.05]). Notwithstanding the high heterogeneity (I^2 = 89%), the results remain statistically significant (P = 0.03). On the other hand there is no evidence of a statistically significant difference in

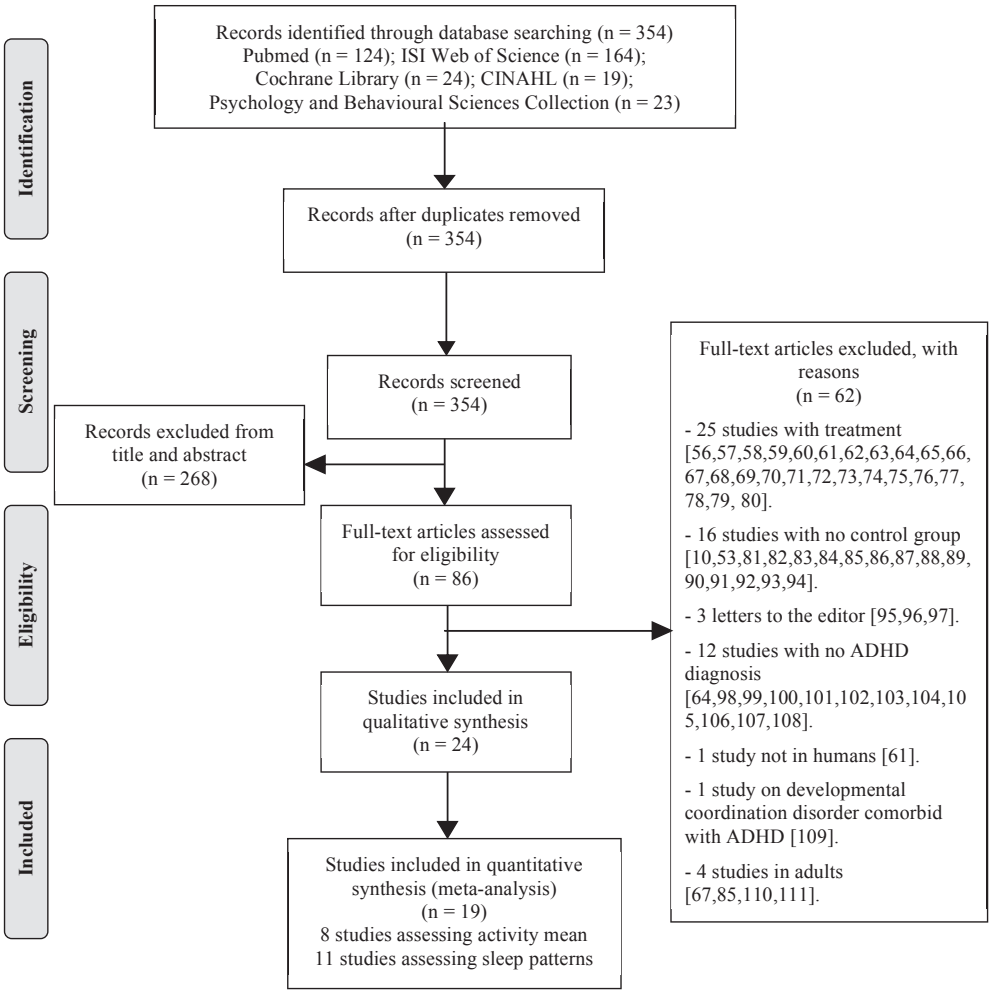


Fig. 1. Flow chart. References of the excluded studies are available in the supplementary material as document S2.

wakefulness between ADHD and TD children judging from the wake after sleep onset data (SMD = 0.06 [−0.16, 0.28]; I^2 = 45%).

Quality assessment

Assessment of the methodological quality of included articles according to the QUADAS criteria is reported in Table 8. Three of the criteria were met by all studies. None of the studies had representative spectrum and reference standard results and index test results were not blinded. Withdrawals were considered insufficiently explained only in one study [41]. The reference standard was not considered acceptable if in the original article it was not accurately reported that all the participants had a visit to an appropriate mental health professional. Visual inspection of the funnel plots was not suggestive of publication bias.

Post-hoc analysis

Since ADHD prevalence was found to be higher in males in various clinical studies with a ratio as high as 10 to 1 [52,53], we decided to perform a subgroup analysis to differentiate studies with 100% males for both patients with ADHD and healthy controls from studies with males and females and to analyze if gender had any impact on the activity mean. For the studies investigating the activity mean, only Tsujii et al. [42] and Alderson et al. [34] had 100% males for both patients with ADHD and healthy controls. The pooled population of males comprised 29 patients with ADHD versus 29 healthy controls (SMD = 0.79 [−0.51, 2.09]). The pooled population of studies with males and females, without Tsujii et al. [42] and Alderson et al. [34], for the activity mean comprised 305 patients with ADHD versus 237 healthy controls (SMD = 0.67 [0.49, 0.84]). This subgroup analysis shows that there is no significant difference in activity mean between patients with ADHD and healthy controls, if we take only studies in males. However, the large confidence interval and the small population included do not allow more in depth considerations. Therefore, at this stage we cannot exclude a gender effect and more research is needed to investigate this issue.

Discussion

The results show evidence for a higher activity mean in ADHD compared to TD children, as expected, while there is no evidence for altered sleep duration. The secondary outcomes show that sleep latency and sleep efficiency appear altered in ADHD while wakefulness periods are not significantly different compared to TD children.

The results of the meta-analysis of activity mean are clear and robust. The low heterogeneity and the jackknife analysis support a finding of higher motor activity in ADHD. The clinical usefulness of this finding is demonstrated in other studies through the positive correlation of the activity mean with poorer levels of performance

Table 1
Included studies.

Study	Participants	Gender (%males)	Age, y (SD)	Diagnostic assessment	Outcomes
Miyahara M et al. 2014	93 ADHD 76 Controls	71%	ADHD: 3.73 Controls: 3.69	ADHDRS WPPSI Mental health professionals (pediatricians, neurologists, school psychologists)	Actigraphy NEPSY
Moreau V et al. *2014*	41 ADHD 41 Controls	58.5%	ADHD: 9.74 (1.68) Controls: 9.56 (1.62)	CBCL CPRS K-SADS-PL	Actigraphy CBCL CSHQ ISI–C Sleep diary
Bessey M et al. *2013*	25 ADHD 25 Controls	88%	ADHD: 8.8 (1.8) Controls: 8.8 (1.9)	CPRS CTRS	Actigraphy SLAQ
Wiebe S et al. *2013*	20 ADHD 46 Controls	64%	ADHD: 9.2 (1.6) Controls: 8.7 (1.1)	CBCL CPRS DISC IV	Actigraphy Polysomnography ESS MSLT Sleep log
Alderson M et al. *2012*	11 ADHD 11 Controls	100%	ADHD: 8.64 (1.29) Controls: 9.45 (1.44)	K-SADS- PL CBCL TRF CSI WISC III-IV (QI > 85)	Actigraphy SSD Choice task Control condition (Microsoft Paint)
Langevin R et al. *2012*	5 ADHD + NTP 5 ADHD 5 Controls	80%	Total: 8.13	DSM-IV	Actigraphy Sleep agenda SWAN-F
Gruber R et al. *2011*	11 ADHD 32 Controls	63%	ADHD: 8.7 (1.3) Controls: 8.8 (1.3)	DISC-IV CBCL CPRS WISC-IV (QI > 80)	Actigraphy Polysomnography ESS Sleep log CPT
Kam HJ et al. *2011*	10 ADHD 7 Controls	53%	ADHD: 7.2 (0.63) Controls: 7.5 (0.53)	CBCL K-ARS K-SADS-PL	Actigraphy
Mullin BC et al. *2011*	13 BD 14 ADHD 21 Controls	58%	BD: 14.4 (2.1) ADHD: 15.1 (2.1) Controls: 14.1 (2.0)	K-SADS- PL P- YMRS	Actigraphy Sleep diary
Licht CA et al. *2009*	9 ADHD 9 Controls	83%	ADHD: 9.33 (1.00) Controls: 9.11 (1.17)	PPVT-R (>85) Barkley's ADHD Clinical parent interview ADDES-S ADDES-H	Actigraphy
Owens J et al. *2009*	107 ADHD 46 Controls	69%	ADHD: 10.2 (2.0) Controls: 10.3 (2.6)	ADHDRS K-SADS PL CGI S WISC IV (QI > 80)	Actigraphy Electronic diaries
Rapport MD et al. *2009*	12 ADHD 11 Controls	100%	Total: 9.04 (1.36)	K-SDAS PL CBCL TRF CSI WISC III-IV	Actigraphy Phonologic working memory task Visuospatial working memory task Controls (Microsoft Paint)
Tsujii N et al. *2009*	18 ADHD 10 PDD + hyperactivity (3 Asperger, 7 unspecified PDD) 18 Controls	100%	ADHD: 9.33 (1.41) PDD: 9.2 (1.75) Controls: 9.17 (1.2)	Clinical Interview CBCL TRF WISC III (QI > 70)	Actigraphy
Wood AC et al. *2009*	116 ADHD (combined type) 119 Siblings 218 Controls	82%	ADHD: 11.90 (2.74) Siblings: 11.51 (2.85) Controls: 12.76	PACS CPRS CTRS	Actigraphy
Halperin JM et al. *2008*	98 ADHD 85 Controls	100%	ADHD: 18.30 (1.60) Controls: 18.51 (1.66)	K-SADS PL	Actigraphy WAIS III Stroop color-word test CPT
Hvolby A et al. *2008*	45 ADHD 64 other psychiatric diagnoses 97 Controls	74%	ADHD: 8.4 Psychiatric control group: 8.6 Controls: 8	K-SADS PL ADHD- RS	Actigraphy, Sleep diaries
Gruber R et al. *2004*	24ADHD 25 Controls	100%	ADHD: 8.94 (1.25) Controls: 8.83 (1.01)	K-SADS PL	Actigraphy Sleep Habits Questionnaire NES
Salbach H et al. *2002*	31 ADHD 31 Controls	–	ADHD: 9.1 Controls: 9.6	ICD 10 Achenbach teachers questionnaire CTRS DIPS	Actigraph Delay Gratification Test (DGT) Continuous Performance Test (CPT) TRF CTRS

Table 1 (*continued*)

Study	Participants	Gender (%males)	Age, y (SD)	Diagnostic assessment	Outcomes
Corkum P et al. *2001*	25 ADHD 25 Controls	80%	ADHD: 9.12 (1.42) Controls: 9.72 (1.31)	Parent and teacher interviews Child assessment	Actigraphy CSP-Q Sleep diaries
Dane AV et al. *2000*	20 ADHD-I 22 ADHD-C 22 Controls	76.5%	ADHD I: 9.28 (1.44) ADHD C: 9.11 (1.47) Controls: 9.14 (1.38)	Clinical diagnostic protocol PICS TTI Ontario Child Helath Study Scale	Actigraphy IOWA Conner's rating scale
Gruber R et al. *2000*	38 ADHD 64 Controls	100%	ADHD: 9.6 (2.7) Controls: 9.4 (1.7)	ADHD Symptom checklist CBCL	Actigraphy Daily sleep logs
Konrad K et al. *2000*	31 ADHD 27 TBI 26 Controls	68%	ADHD: 10.5 (1.6) TBI: 10.6 (1.7) Controls: 10.2 (1.2)	K-DIPS PICS FBB-HKS	Stop signal task Delayed response task Actigraphy
Inoue K et al. *1998*	20 ADHD 52 Controls	100%	ADHD: 9 Controls: 9.5	DSM-III-R	CPT WISC-R MFFT Actigraphy
Halperin JM et al. *1992*	31 ADHD 53 Patients No ADHD 18 Controls	81%	ADHD: 9.6 (1.83) No ADHD: 10.1 (1.7) Controls: 9.1 (1.8)	CBCL CTQ	Actigraphy RCPM PPVT-R WRAT-R PIAT-R CPT

Note: **ADDES-H** = attention-deficit disorders evaluation scale, home version; **ADDES-S** = attention-deficit disorders evaluation scale, school version; **ADHDRS** = attention-deficit/hyperactivity disorder rating scale; **BD** = bipolar disorder; **CBCL** = child behavior checklist; **CGI S** = clinical global impression- severity of illness; **CPT** = continuous performance test; **CPRS** = Conners' parent rating scales; **CTRS** = Conners' teacher rating scale; **CSHQ** = children's sleep habits questionnaire; **CSI** = child symptom inventory-parent and teacher; **CSP-Q** = child sleep questionnaire, parent version; **CTQ** = Conner's teacher questionnaire; **DISC IV** = diagnostic interview schedule for children; **ESS** = Epworth sleepiness scale; **FBB-HKS** = questionnaire for teacher e hyperkinetic syndrome; **ISIeC** = insomnia severity index for children; **K-ARS** = ADHD rating scale, korean edition; **K-DIPS** = diagnostisches interview fur psychische storungen im kindesalter; **K-SADS-PL** = kiddie-sads-present and lifetime version; **MFFT** = matching familiar figure test; **Microsoft paint** = the paint program served as pre- and postconditions to control for potential within-day fluctuations in activity level (es. fatigue effects); **MSLT** = multiple sleep latency test; **NEPSY** = developmental neuropsychological assessment; **NES** = neurobehavioral evaluation: finger tapping, digit span forward, digit span backward, reaction time, symbol- digit substitution task, CPT; **P-YMRS** = parent version of the Young mania rating scale; **PACS** = parental account of childhood symptoms; **PDD** = pervasive developmental disorder; **PIAT** = Peabody individual achievement test-revised; **PICS** = parent interview for child symptoms; **PPVT-R** = Peabody picture vocabulary test-revised; **RCPM** = Raven's colored progressive matrices; **SLAQ** = sleep lab adaption questionnaire; **SSD** = stop-signal delays; **SWAN- F** = symptoms and normal behavior questionnaire; **TBI** = traumatic brain injury; **TRF** = teacher report form; **TTI** = teacher telephone interview; **WAIS- III** = Weschler adult intelligence scale, third edition; **WISC-III** = Wechsler intelligence scale for children- III; **WISC-IV** = Wechsler intelligence scale for children-IV; **WPPSI** = Weschler primary and preschool intelligence test; **WRATR** = wide range achievement test-revised.

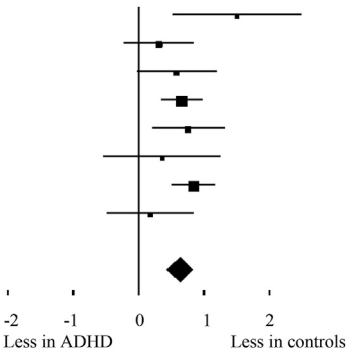
Table 2
Methodological aspects of actigraphic devices in studies included.

Study	Type of device	Where worn	When recorded	Storage rate used
Miyahara M et al. *2014*	AM7164; Actigraph, Fort Walton Beach, FL	Non dominant ankle, waist	Experimental session	N.R.
Moreau V et al. *2014*	AW-64 Mini-Mitter	Wrist	5 nights	0.5 min epoch
Bessey M et al. *2013*	Basic Mini Motionlogger; Ambulatory Monitoring Inc., NY	Wrist	6 nights + sleep lab	N.R.
Wiebe S et al. *2013*	AW-64 Mini-Mitter	Non dominant wrist	5 nights	1 min epoch
Alderson M et al. *2012*	Basic Mini Motionlogger; Ambulatory Monitoring Inc., NY	Non dominant wrist	Experimental session	1 min epoch
Langevin R et al. *2012*	AW-64 Mini-Mitter	Non dominant wrist	2 measuring times, 5 weekdays each	N.R.
Gruber R et al. *2011*	AW-64 Mini-Mitter	N.R.	24 h	1 min epoch
Kam HJ et al. *2011*	LIG NEX1 Co., Ltd., Yangin, Korea	Non dominant wrist	During a school lesson	1 min epoch
Mullin BC et al. *2011*	AW-64 Mini-Mitter	Non dominant wrist	4 nights	1 min epoch
Licht CA et al. *2009*	Computer science and Applications (CSA)/Manufacturing Technology, Inc.	Waist	14 d (8–15) 24 h a day	1 min epoch
Owens J et al. *2009*	AW-64 Mini-Mitter	Non dominant wrist	3 visits in 10–24 nights	1 min epoch
Rapport MD et al. *2009*	Basic Mini Motionlogger; Ambulatory Monitoring Inc., NY	Non dominant wrist, ankles	Experimental session	1 min epoch
Tsujii N et al. *2009*	Mini Motionlogger; Ambulatory Monitoring Inc., NY	Non dominant wrist	1 wk at school	1 min epoch
Wood AC et al. *2009*	MTI Health services Version 323 Health One Technology, Pensacola, FL	Dominant leg, waist	2 h with a 25 min break	1 min epoch
Halperin JM et al. *2008*	CSA activity monitor	Non dominant ankle, waist	Experimental session	1 min epoch
Hvolby A et al. *2008*	Mini Motionlogger; Ambulatory Monitoring, Inc, Ardsley, NY	Dominant wrist	5 nights	N.R.
Gruber R et al. *2004*	Mini Motionlogger; Ambulatory Monitoring Inc. Ardsley, NY	Non dominant wrist	5 nights	1 min epoch
Salbach H et al. *2002*	N.R.	N.R.	N.R.	N.R.
Corkum P et al. *2001*	Mini Motionlogger; Ambulatory Monitoring Inc., NY	Non dominant wrist	7 nights	1 min epoch
Dane AV et al. *2000*	Ambulatory Monitoring Inc. 1996	Non dominant wrist	2 h period and a second 2 h interval	1 min epoch
Gruber R et al. *2000*	N.R.	N.R.	5 nights	N.R.
Konrad K et al. *2000*	Cambridge Neurotechnology, Version 2.56	Preferred arm	Experimental session	0.25 min epoch
Inoue K et al. *1998*	N.R.	Waist	Experimental session	1 min epoch
Halperin JM et al. *1992*	N.R.	Waist	Experimental session	N.R.

N.R. = not reported.

Table 3
Activity mean.

Study	ADHD			TD			Weight	Std. Mean difference IV, random, 95% CI
	Mean	SD	Total	Mean	SD	Total		
Alderson M et al. *2012*	4751.5	2579.9	11	1753.9	818.4	11	5.0%	1.51 [0.54, 2.48]
Dane AV et al. *2000*	224.8	15.8	42	218.6	25.9	22	15.6%	0.31 [−0.21, 0.83]
Halperin JM et al. *1992*	32.0	16.0	31	22.5	16.0	18	12.4%	0.58 [−0.01, 1.18]
Halperin JM et al. *2008*	1.7	0.4	98	1.4	0.3	85	36.1%	0.66 [0.36, 0.96]
Konrad K et al. *2000*	5203.0	2293.0	31	3611.0	1772.0	26	14.5%	0.76 [0.22, 1.30]
Licht CA et al. *2009*	411.5	129.5	10	365.2	117.6	10	6.0%	0.36 [−0.53, 1.24]
Miyahara M et al. *2014*	487.13	362.57	93	236.96	183.71	76	24.5%	0.84 [0.53, 1.16]
Tsujii N et al. *2009*	214.5	14.4	18	210.6	26.7	18	10.4%	0.18 [−0.48, 0.83]
Total (95% CI)			334			266	100.0%	0.65 [0.45, 0.84]



Notes: ADHD = attention deficit/hyperactivity disorder; CI = confidence interval; IV = inverse variance method; SD = standard deviation; TD = typically developing.
Heterogeneity: $Tau^2 = 0.02$; $Chi^2 = 8.68$, df = 7 (P = 0.28); $I^2 = 19\%$.
Test for overall effect: Z = 6.41 (P < 0.00001).

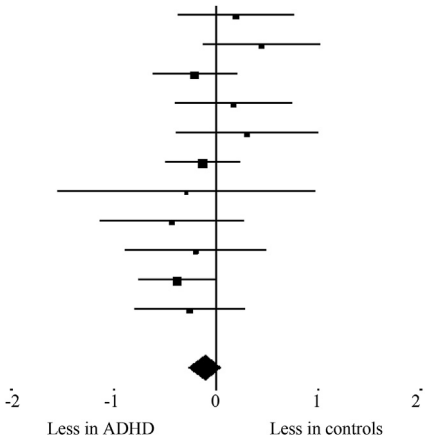
and lower levels of functioning [54,55]. The sensitivity analysis shows strong evidence of a large effect during structured experimental sessions. As a whole, these findings suggest that actigraphy might be used by the clinician in the monitoring of activity during structured sessions (e.g., during psychological tests in outpatient setting) and suggest that more research is warranted to understand whether children with ADHD move more than TD children throughout the whole day.

Sleep duration is not significantly different between ADHD and TD children and there is homogeneity between the studies ($I^2 = 7\%$). However, the jackknife analysis on sleep duration is significant (SMD = −0.10 [−0.15, −0.05]) and this means that some evidence for lower sleep duration in ADHD might derive from more and larger studies (see Table S4). Nevertheless, we believe that the sample analysed by our meta-analysis (297 ADHD and 426 TD) is sufficiently large and that although important for research purposes, smaller differences in sleep duration are unlikely to be clinically meaningful.

The secondary outcomes indicate an altered pattern of sleep. As we expected, the secondary outcomes present with high heterogeneity and are less reliable than the primary ones. This is because actigraphy is not very sensitive for wakefulness periods [56] and sleep efficiency is intimately correlated to wake after sleep onset. Indeed sleep latency presents with a high heterogeneity, but it is not considered as a very reliable parameter in actigraphy [22]. In order to address heterogeneity we used the random effects model, which is more conservative than the fixed effects model. Notwithstanding this, the significant results tell us that by using actigraphy we might find an altered sleep pattern in ADHD children, even if they do not present with sleep problems and even if

Table 4
Sleep duration.

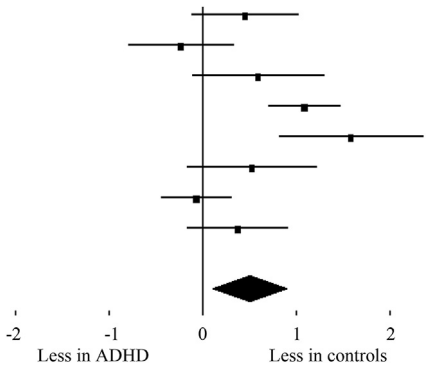
Study	ADHD			TD			Weight	Std. Mean difference IV, random, 95% CI
	Mean	SD	Total	Mean	SD	Total		
Bessey M et al. *2013*	571.0	42.2	25	562.2	47.6	25	8.0%	0.19 [-0.36, 0.75]
Corkum P et al. *2001*	569.6	33.0	25	552.9	41.0	25	7.9%	0.44 [-0.12, 1.00]
Gruber R et al. *2000*	514.3	44.5	38	522.0	30.4	64	14.5%	−0.21 [-0.61, 0.19]
Gruber R et al. *2004*	537.7	27.4	24	532.0	36.8	25	7.9%	0.17 [-0.39, 0.73]
Gruber R et al. *2011*	487.7	27.2	11	478.8	29.5	32	5.4%	0.30 [-0.39, 0.99]
Hvolby A et al. *2008*	555.0	42.0	45	560.0	36.0	97	18.1%	−0.13 [-0.48, 0.22]
Langevin R et al. *2012*	9.4	0.2	5	9.5	0.5	5	1.7%	−0.29 [-1.54, 0.96]
Moreau V et al. *2014*	475.6	36.9	10	490.6	33.3	41	5.2%	−0.43 [-1.13, 0.26]
Mullin BC et al. *2011*	424.2	67.3	14	436.9	58.3	21	5.5%	−0.20 [-0.88, 0.48]
Owens J et al. *2009*	517.0	46.1	80	533.8	40.0	45	16.9%	−0.38 [-0.75, −0.01]
Wiebe S et al. *2013*	474.6	33.6	20	484.1	37.6	46	8.9%	−0.26 [-0.78, 0.27]
Total (95% CI)			297			426	100.0%	−0.10 [-0.26, 0.06]



Notes: ADHD = attention deficit/hyperactivity disorder; CI = confidence interval; IV = inverse variance method; SD = standard deviation; TD = typically developing.
Heterogeneity: $Tau^2 = 0.01$; $Chi^2 = 10.79$, df = 10 (P = 0.37); $I^2 = 7\%$.
Test for overall effect: Z = 1.20 (P = 0.23).

Table 5
Sleep latency.

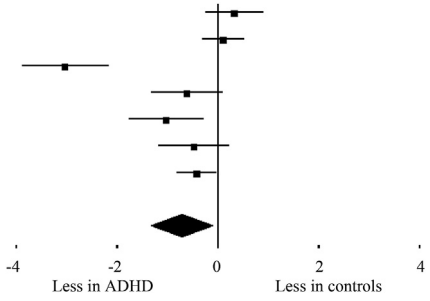
Study	ADHD			TD			Weight	Std. Mean difference IV, random, 95% CI
	Mean	SD	Total	Mean	SD	Total		
Bessey M et al. *2013*	31.66	24.43	25	22.05	16.82	25	12.6%	0.45 [−0.11, 1.01]
Corkum P et al. *2001*	22.4	9.0	25	25.2	14.0	25	12.7%	−0.23 [−0.79, 0.32]
Gruber R et al. *2011*	43.01	23.32	11	30.26	20.4	32	11.1%	0.59 [−0.11, 1.29]
Hvolby A et al. *2008*	26.3	16.3	45	13.5	8.9	97	14.8%	1.08 [0.71, 1.46]
Moreau V et al. *2014*	38.26	13.83	10	20.81	10.07	41	10.5%	1.58 [0.82, 2.34]
Mullin BC et al. *2011*	28.7	18.0	14	20.8	12.1	21	11.2%	0.52 [−0.16, 1.21]
Owens J et al. *2009*	31.44	23.07	80	32.94	17.39	45	14.9%	−0.07 [−0.44, 0.30]
Wiebe S et al. *2013*	32.1	15.9	20	25.3	19.0	46	13.0%	0.37 [−0.16, 0.90]
Total (95% CI)			230			332	100.0%	0.51 [0.10, 0.92]



Notes: ADHD = attention deficit/hyperactivity disorder; CI = confidence interval; IV = inverse variance method; SD = standard deviation; TD = typically developing.
Heterogeneity: $Tau^2 = 0.27$; $Chi^2 = 33.29$, df = 7 ($P < 0.0001$); $I^2 = 79\%$.
Test for overall effect: $Z = 2.44$ ($P = 0.01$).

Table 6
Sleep efficiency.

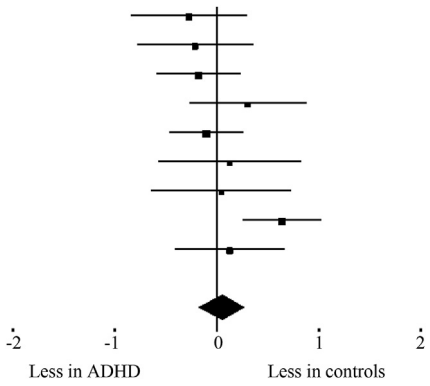
Study	ADHD			TD			Weight	Std. Mean difference IV, random, 95% CI
	Mean	SD	Total	Mean	SD	Total		
Bessey M et al. *2013*	83.35	10.42	25	79.9	10.76	25	14.7%	0.32 [−0.24, 0.88]
Gruber R et al. *2000*	93.5	3.9	38	93.1	4.1	64	15.5%	0.10 [−0.30, 0.50]
Gruber R et al. *2004*	62.3	10.75	24	93.3	9.34	25	12.8%	−3.03 [−3.87, −2.19]
Gruber R et al. *2011*	76.49	4.0	11	79.22	4.45	32	13.8%	−0.62 [−1.32, 0.08]
Moreau V et al. *2014*	78.21	3.37	10	82.03	3.71	41	13.6%	−1.03 [−1.75, −0.31]
Mullin BC et al. *2011*	80.2	6.1	14	82.8	4.7	21	13.9%	−0.48 [−1.17, 0.21]
Owens J et al. *2009*	84.0	5.0	80	86.0	4.0	45	15.7%	−0.43 [−0.80, −0.06]
Total (95% CI)			202			253	100.0%	−0.69 [−1.32, −0.05]



Notes: ADHD = attention deficit/hyperactivity disorder; CI = confidence interval; IV = inverse variance method; SD = standard deviation; TD = typically developing.
Heterogeneity: $Tau^2 = 0.64$; $Chi^2 = 53.41$, df = 6 ($P < 0.00001$); $I^2 = 89\%$.
Test for overall effect: $Z = 2.12$ ($P = 0.03$).

Table 7
Wake after sleep onset.

Study	ADHD			TD			Weight	Std. Mean difference IV, random, 95% CI
	Mean	SD	Total	Mean	SD	Total		
Bessey M et al. *2013*	95.27	57.8	25	111.47	58.31	25	9.9%	−0.27 [−0.83, 0.28]
Corkum P et al. *2001*	15.1	7.3	25	16.6	6.6	25	9.9%	−0.21 [−0.77, 0.34]
Gruber R et al. *2000*	2.7	1.6	38	3.0	1.7	64	14.1%	−0.18 [−0.58, 0.22]
Gruber R et al. *2004*	2.2	1.3	24	1.8	1.3	25	9.8%	0.30 [−0.26, 0.87]
Hvolby A et al. *2008*	2.7	1.2	45	2.8	0.8	97	15.7%	−0.11 [−0.46, 0.25]
Moreau V et al. *2014*	65.44	20.69	10	63.27	15.75	41	7.4%	0.13 [−0.56, 0.82]
Mullin BC et al. *2011*	56.3	17.4	14	55.5	19.2	21	7.7%	0.04 [−0.63, 0.72]
Owens J et al. *2009*	56.7	19.64	80	44.49	17.93	45	15.0%	0.64 [0.26, 1.01]
Wiebe S et al. *2013*	87.4	27.1	20	84.4	21.8	46	10.6%	0.13 [−0.40, 0.65]
Total (95% CI)			281			389	100.0%	0.06 [−0.16, 0.28]



Notes: ADHD = attention deficit/hyperactivity disorder; CI = confidence interval; IV = inverse variance method; SD = standard deviation; TD = typically developing.
Heterogeneity: $Tau^2 = 0.05$; $Chi^2 = 14.44$, df = 8 ($P = 0.07$); $I^2 = 45\%$.
Test for overall effect: $Z = 0.54$ ($P = 0.59$).

Table 8
Table of bias.

	Representative spectrum?	Acceptable reference standard?	Acceptable delay between tests?	Partial verification avoided?	Differential verification avoided?	Incorporation avoided?	Reference standard results blinded?	Index test results blinded?	Relevant clinical information?	Uninterpretable results reported?	Withdrawals explained?
Miyahara M et al. *2014*	−	?	+	−	−	+	−	−	+	+	+
Moreau V et al. *2014*	−	+	+	+	+	+	−	−	+	+	+
Bessey M et al. *2013*	−	?	+	?	+	+	−	−	+	+	+
Wiebe S et al. *2013*	−	+	+	+	+	+	−	−	+	+	+
Alderson M et al. *2012*	−	+	+	+	+	+	−	−	+	?	+
Langevin R et al. *2012*	−	+	+	+	?	+	−	−	+	−	+
Gruber R et al. *2011*	−	+	+	+	+	+	−	−	+	+	+
Kam HJ et al. *2011*	−	+	+	+	+	+	−	−	+	+	+
Mullin BC et al. *2011*	−	+	+	+	+	+	−	−	+	+	+
Licht CA et al. *2009*	−	+	+	+	+	+	−	−	+	+	+
Owens J et al. *2009*	−	+	+	+	+	+	−	−	+	−	+
Rapport MD et al. *2009*	−	+	+	+	+	+	−	−	+	+	−
Tsujii N et al. *2009*	−	?	+	?	+	+	−	−	+	+	+
Wood AC et al. *2009*	−	?	+	+	?	+	−	−	+	−	+
Halperin JM et al. *2008*	−	+	+	+	+	+	−	−	+	?	+
Hvolby A et al. *2008*	−	?	+	+	?	+	−	−	+	+	+
Gruber R et al. *2004*	−	+	+	+	+	+	−	−	+	+	+
Salbach H et al. *2002*	−	+	+	+	+	+	−	−	+	−	+
Corkum P et al. *2001*	−	?	+	+	+	+	−	−	+	?	+
Dane AV et al. *2000*	−	+	+	+	+	+	−	−	+	+	+
Gruber R et al. *2000*	−	−	+	−	−	+	−	−	+	−	+
Konrad K et al. *2000*	−	+	+	+	+	+	−	−	+	+	+
Inoue K et al. *1998*	−	?	?	?	?	+	−	−	+	+	+
Halperin JM et al. *1992*	−	?	+	+	+	+	−	−	+	?	+

"+" = low risk of bias; "-" = high risk of bias; "?" = unclear risk of bias.

not pharmacologically treated. Moreover, actigraphic studies have shown that night-to-night variability in sleep schedule measures (e.g., sleep onset, sleep duration) is easy to differentiate between ADHD and control groups [17,46].

This meta-analysis has some limitations. Firstly, even if on the one hand statistical analyses indicate that our sample size was sufficient for the detection of significant effects for the activity mean in experimental sessions, on the other hand if we take into account only the small studies on the 24 h activity mean the size of our sample is underpowered. Therefore for the activity mean in the 24 h we suggest our results be considered with caution. Secondly, our results may be considered difficult to generalise due to the fact that the original studies used different actigraphic devices and that there is high variability among different actigraphs. However we used the SMD and the random effect model in order to be able to address this heterogeneity. Thirdly, the majority of the included studies had sleep problems or other medical conditions as exclusion criteria. Therefore it should be highlighted that our meta-analysis is valid for a subgroup of children with ADHD without medical comorbidities. Fourthly, the actigraphs are not the gold standard to evaluate sleep problems. Indeed we know that actigraphy allows the reliable, continuous recording of a child's sleep in his or her own bed, but does not allow recording of sleep architecture. However, actigraphs are handy, and in ADHD they can be easily used for the monitoring of sleep and activity in outpatient settings.

In conclusion, we think that clinicians might use actigraphy in ADHD children for the monitoring of sleep patterns and for motor activity during structured experimental sessions and for the monitoring of motor activity and sleep patterns during treatment with MPH [25], while we have only limited evidence to support the use of actigraphy in the diagnosis or as a screening tool in ADHD [37].

In this meta-analysis, we have reviewed whether actigraphy shows consistency for the monitoring of motor activity and sleep in ADHD children. We believe these findings open up new perspectives on assessment, management and therapeutic follow up in ADHD.

Practice points

In patients with ADHD actigraphy may be useful to:

1. Monitor activity mean and its clinical evolution in an outpatient setting;
2. Monitor sleep problems, mainly sleep latency and efficiency.

Research agenda

In patients with ADHD there is a need for studies which:

1. Examine if actigraphy is efficient as a monitoring tool of activity and sleep in ambulatory setting;
2. Investigate actigraphic motor activity during 24 h;
3. Explore whether altered actigraphic parameters should be treated and if yes, how.

Conflicts of interest

The authors declare no conflict of interests.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.smrv.2015.04.002.

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