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A review of developmental consequences of poor sleep in childhood

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ABSTRACT

Sleep is a fairly diverse and complex construct to operationalize in a scientific and naturalistic context. We report a systematic review and meta-analysis of reviews published in the last 5 years on poor sleep and developmental outcomes. Following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines, 42 articles (or 1117 studies) qualified. They reported outcomes related to poor sleep investigated as sleep disorders (38.1%), sleep ‘in general’ (26.2%), sleep duration (23.8%), in terms of circadian rhythm (4.8%), intra-individual variability (2.4%), and napping (2.4%). Sleep was primarily subjectively reported (30.2%), yet the methodology of sleep assessment was often neither tabulated nor discussed. Overall, most papers had a health-scope, being primarily weight problems expressed as body mass index. Its relationship with performance was measured with the Wechsler intelligence tests, the child behavior checklist and the continuous performance test, whereas meta-analytic papers specifically focused on cognition with sleep disorder (i.e. sleep-disordered breathing; 38.6%), on health (i.e. weight) with sleep duration (25%) and behavior with sleep ‘in general’ (15.9%), having a high true variance. Nevertheless, an aggregated effect size d of 0.35 (95% confidence interval: 0.27–0.42) suggests that poor sleep is moderately affecting a child’s performance and health.

In conclusion, poor sleep can no longer be disregarded, yet methodologies that are more rigorous and a scope beyond health may foster a better understanding of the role of (poor) sleep across childhood neurodevelopment.

Keywords:

Sleep quantity

Sleep problem

Circadian misalignment

Cognition

Behavior

Socio-emotional development

POOR SLEEP

Relative to sleep duration and the effects of sleep disorders, there has been insufficient emphasis on other aspects of sleep adequacy such as circadian alignment and environmental impacts on childhood sleep. The majority of scientific studies appear to focus on sleep duration, while especially in childhood this may be challenging. For example, a cut-off of 10 h sleep for school-aged children creates ‘arbitrary’ categories, which may not always turn out to be suitable for every child included (Supplementary Fig. S1). Superimposed on the schemes of the guidelines by the National Sleep Foundation [1] and the American Academy of Sleep Medicine [2] (Supplementary Fig. S1) are the meta-analyzed sleep patterns generated by Galland et al. [3]. This shows that the averaged sleep duration of, for instance, school-aged children falls at the lower boundaries of the recommended number of nightly hours across the age ranges, and in particular below such a 10-h cut-off. Notwithstanding, the averaged lower limits of sleep duration – or the ‘reality’ in the absence of large-scale objective sleep studies given that subjective reports tend to be overestimations [4] – nearly always fall in the questionable zones across childhood. As a result, should we question the guidelines, the averages (hence reality) or the methodology? Indeed, the cut-offs, and especially sleep recommendations, have been and are heavily discussed [2,5–7]. For instance, Matticcianni et al. [8–12] have extensively reported on sleep duration now and in the past. Similarly, consensus statements regarding indicators of good sleep quality (e.g., sleep latency, number of awakenings >5 min, wake after sleep onset, and sleep efficiency) at different ages across the lifespan have been published, and may aid our observation of poor sleep [6].

Given that the sleep-state is a highly dynamic process, which is rapidly developing in the first few years of life, two recent trends towards a better understanding of the role of poor sleep in pediatrics can be noticed. One trend is the focus on daytime sleep behavior in young children. Napping [13] indeed facilitates simple experimental manipulations which appear less intrusive to family life. Yet, it remains challenging to generalize such findings to nighttime sleep due to possible differences in sleep architecture, circadian timing, developmental aspects and ecological validity. Another trend is

the interest in the microstructure of sleep, and especially its association with cognitive performance (e.g., [14–18]). Likely, a growing interest in brain mapping, such as by the US BRAIN and the Human Brain Project of the European Union, may further intensify this research topic. As a side-effect, there could be an upsurge of objective sleep studies in typically developing children. This may, in turn, improve our understanding of the role of (poor) sleep across development and underpin the current consensus guidelines.

Consequently, when reflecting upon the concept of poor sleep, we might consider it in terms of sleep quantity, sleep quality and sleep timing (or circadian alignment) with their variability in relation to wake behavior (Supplementary Fig. S2). Alternatively, the wake-state cannot be fully understood without the sleep-state (and vice versa). Better understanding of their reciprocal influence, and especially the impact on subsequent daytime performance, warrants a comprehensive operationalization of sleep. That is, when determining the timing, quantity and quality of sleep, both homeostatic and circadian processes modulated by hypothalamic areas, and biopsychosocial factors, are believed to interact [19–22]. Their dysfunction, perhaps experienced as ‘hyper’-somnolence or challenge-seeking wakefulness [23,24] is universally perceived to affect daytime performance. Despite consensus guidelines, and a growing body of scattered findings, many questions regarding the role of (poor) sleep in childhood development are left unanswered.

In pediatric research, we are moreover cognizant of intra- and inter-individual vulnerabilities in development. The interrelation of sleep with such developmental salience has not yet received the scientific attention it deserves; accordingly, it is potentially overlooked in the conceptualization of poor sleep is our individual sleep need (Supplementary Fig. S2). Hence, the operationalization of the multidimensional concept of sleep should involve sleep behaviors (e.g., lights out, bedtime, timing of sleep, napping, week versus weekend changes), sleepiness and sleeplessness (i.e. its degree, timing, and duration), dim light melatonin onset, sleep macrostructure and microstructure parameters. Comprehensive assessment may elucidate its role throughout development, while detailed operationalization, and prolonged objective measurement, may support the advancement of novel non-pharmacological treatment models in health sciences, based on manipulating sleep in its entirety.

The purpose of the review is to summarize current knowledge regarding the influence of poor sleep, in its various forms, on childhood development and to identify deficiencies and areas for future exploration. We will focus on reviews and meta-analyses published in the last 5 years.

METHODS

Procedure

The searches were performed in PubMed, Web of Science, and Cochrane Library Reviews focusing on literature of the last 5 years and ‘reviews/meta-analyses’ only. All database searches were updated on 01 June 2018 using the following search terms: “sleep*”, “health OR cognition/learning/school performance/intelligence OR behavior OR social/emotional/socio-emotional OR sensorimotor/sensory/motor”, and “child” (i.e. neonate – adolescent)* with filters for English language.

The inclusion of the literature was based on systematic reviews and meta-analyses focusing on sleep duration, sleep problems, sleep regularity, circadian rhythm and sleep habits (i.e. potential determinants of poor sleep). These reviews should summarize the association between poor sleep and childhood development. Child development entails the biological and psychological developments in human beings between birth and the end of adolescence. Studies were excluded if they focused on participants with mental or physical illness, or described interventions/treatments. Letters, original papers and personal opinions were not included. Applying the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines [25], the following steps were undertaken: (1) the title/keywords were assessed, if the article contained information regarding the rationale of our review; (2) the remaining titles/abstracts were screened; and (3) the articles themselves were read for appropriateness; and (4) relevant data was abstracted (see Fig. 1).

Statistical analysis

Systematic reviews were quantified when possible. Meta-analyses were performed using Comprehensive Meta-Analysis software (version 3.3.070; Biostat, Englewood, NJ, USA).

Meta-analytic results (hereafter abstracted effect sizes (aES)) were re-calculated into one metric (Cohen's d), such that a positive ES indicates adversity. Results reflect relative weight under the random effects model. The value of I^2 , the proportion of the observed variation that is true, ranges from 0% to 100% with 0% indicating no heterogeneity, 25% low heterogeneity, 50% moderate heterogeneity, and 75% high heterogeneity. The prediction interval of I^2 expresses the range of the common (shared) effect (%) by the included studies.

RESULTS

Paper characteristics

Of the 792 references for cognition, behavior, socio-emotional, healthy and sensorimotor development (see Fig. 1), 362 remained for more detailed processing. After reading, 42 were retained for data abstraction (Table 1, Supplementary Tables S1–S3).

These review/meta-analytic papers involved 1117 studies investigating poor sleep and neurodevelopmental outcomes. That is, they reviewed: sleep disorders (38.1%), sleep ‘in general’ (e.g., sleep quality; 26.2%), sleep duration (23.8%), circadian rhythm (4.8%), intra-individual variability (2.4%) and napping (2.4%). When categorizing the papers on their reported sleep assessment, 30.2% involved subjective measurements of sleep, 22.5% involved objective measurements of sleep (e.g., polysomnography and actigraphy) and in 48.7% of the review/meta-analytic papers, it was not clearly tabulated whether they reported on subjective/objective measures of sleep. Overall, most papers had a health-scope, being primarily weight problems expressed as body mass index (Supplementary Table S2). The relationship between ‘poor’ sleep and performance was chiefly measured with the Wechsler series, the child behavior checklist and the continuous performance test (Supplementary Table S3).

Overall, a moderate effect (number of aESs = 39, $d = 0.35$, 95% confidence interval (CI): 0.27–0.42; z -value = 9.5, $p < 0.00001$; $I^2 = 97.5$, 95% prediction interval (PI): 0–92%) was found, suggesting that, given the current methodology, poor sleep adversely affected health and performance across childhood. The explained variance by this broad collection of studies was 21.4%. It is noteworthy that, when grouping the aESs, the focus of the papers was shown to be 38.6% on cognition with sleep disorder (i.e. sleep-disordered breathing (SDB)), 25% on health with sleep duration, and for 15.9% on behavior with sleep ‘in general’.

Healthy development

Meta-analysis

The aggregated effect size (d) for 'health' based on nine aESs was 0.28 (95% CI: 0.23–0.34; z -value=9.8, $p<0.00001$; $I^2=85.4$, 95% PI: 9.9–45.9%). Two hot-topics could be distinguished: the relationship between sleep duration and obesity [26–32], and the relationship between SDB and performance [33–36]. Moreover, two meta-analyses investigated the association between SDB and obesity/cardiovascular risk [37,38], and another two papers, despite being intervention studies for SDB, reported baseline aES for neuropsychological performance [33,39].

Possibly due to the era, one meta-analysis studied the current evidence towards the association between media-usage with sleep [40].

Meta-analysis of longitudinal studies as well as cross-sectional studies, showed that short sleep duration in children is significantly associated with overweight/obesity [26–28,31]. In fact, with every 1 h/day increment in sleep duration [30], the risk of overweight/obesity was found to reduce by 21%. This was echoed by a recent meta-analysis [32] suggesting a heightened risk ratio especially in middle childhood for short sleep. Others [27] showed that both short sleep duration and poor sleep quality should be considered, and the latter is especially adversative in the youngest. However, when looking at the studies tabulated, the arbitrary cut-offs overlap in their lower and upper boundaries of both the sleep and weight measures, which may blur conclusions. Insufficient data could be abstracted from Quist et al. [29] to be included in our meta-analysis. Yet, their findings support the association between inadequate sleep and health problems, e.g. in terms of abdominal adiposity, insulin sensitivity, blood lipids and blood pressure.

Pooled aESs generated from studies investigating SDB and performance suggest that attention deficit hyperactivity disorder symptoms [35], executive dysfunction measured objectively and subjectively [36], and academic underperformance [34] are related to SDB. Ehsan et al. [37] reported an increased daytime heart rate in children suffering from SDB (not included in the meta-analysis). Although aES statistics were in the small to medium range, treatment [33,39] showed improved functioning in general. However, a meta-regression [38] showed that residual SDB, especially in those with obesity, remains a double-edged sword (not included in the meta-analysis).

Lastly, in terms of unhealthy 'sedentary' behavior, inadequate sleep quantity, poor sleep quality and excessive daytime sleepiness was associated, even when not using the media devices at night [40].

Systematic reviews

Shochat et al. [41] systematically reviewed 30 adolescent studies on general health outcomes (e.g. health promoting, somatic), overweight and obesity, and health conditions (e.g. pain, cardiovascular, headache, abdominal, metabolic syndrome) per primarily self-reports (25 self-reports, five actigraphy, one mother-report, three objective measure unspecified), and concluded that adequate sleep is associated with a positive health outcome.

Overall, five clusters of systematic reviews investigating poor sleep and health can be outlined: (1) sleep duration and obesity, (2) SDB and performance, (3) sleep and physical activity, (4) sleep disorders and performance, and (5) sleep in young children and performance.

Several reviews concluded a lack of consistent evidence regarding the association between poor sleep and lipid profiles in adolescents [42], cognition, harms/injuries, and cardiometabolic biomarkers [43], or other health indicators (e.g., sedentarism and unhealthy dietary patterns) [44,45]. Each of them further highlighted that the underlying explanatory mechanisms between sleep duration and particularly weight issues are still uncertain.

Regarding the underperformance of children with SDB, receptive and expressive language difficulties [46] and intellectual difficulties [47] were reported. In addition, uncertainties exist here; i.e. which function is most affected and is it 'impairment' when performance falls within the normal range.

A more desirable health is reported in youth when studies interrelating exercise and sleep are systematically reviewed [48,49]. Yet, these associations may be influenced by participants' age, health status, and the mode and intensity of physical activity.

When poor sleep is considered in terms of sleep disorders (excluding SDB), several systematic reviews were found on: bruxism [50], narcolepsy [51,52] and restless legs syndrome [53]. It was stated that snoring, mouth breathing, restless sleep, drooling, stomach position during sleep, and lack of sleep are risk factors related to bruxism in children [50]. Whilst frequently identified as being associated

with hypersomnolence, have been academic dysfunction and emotionally-based problems, such as anxiety, depression and low self-esteem [51,52]. Findings are further inconsistent regarding intellectual performance of children with narcolepsy, where some studies suggest giftedness yet in dissimilar domains [51,52]. Also, restless legs syndrome in children is associated with a number of somatic and neuropsychiatric conditions [53].

Notably due to being primarily ‘caregiver report’ studies and potential multilayered relationships (e.g. attention and concentration problems, or executive dysfunction leading to school difficulties), the question remains whether their dysfunctioning is a (co)morbidity or (co)occurrence.

Inconsistent evidence similarly exists regarding (habitual) napping in infants possibly benefiting cognition, behavior and health. The latter is hypothetically due to the focus being largely on weight gain and obesity rather than healthy growth [13,54]. Alternatively, it is suggested that beyond the age of 2 years, napping influences subsequent sleep macrostructure.

Cognitive development

Around the same period, two reviews [55,56] focused on sleep manipulation, and in particular sleep restriction (Table 1), while only three meta-analyses relating poor sleep to cognitive performance have been published. Tonetti et al. [57] focused on circadian preference (eveningness), Lowe et al. [58] reported human and animal sleep restriction findings, and Short et al. [59] investigated objectively measured sleep duration. Whereas others systematically reviewed, e.g., school start times [60], intra-individual variability in sleep–wake patterns [61], or sleep parameters in preschoolers [62] and infants [54] (Table 1, Supplementary Tables S2, S3).

Meta-analyses

The d for ‘cognition’ based on 19 aES was 0.35 (95% CI: 0.21–0.49; z -value=5.0, p <0.00001; I^2 =98.6, 95% PI: 0–99.8%). Tonetti et al. [57] concluded that evening orientation is associated with worse academic performance, more so in younger students than in university students. Note, these findings were generated primarily from subjective measures (Supplementary Table S2). Lowe et al. [58]

included 17 pediatric studies in addition to adult and animal studies, and reported that overall sleep restriction was associated with cognitive underperformance. Interestingly, they indicated that cumulative days of sleep restriction may increase this negative impact of poor sleep, with the predicted effect sizes inflating from moderate to high. Recalculating across the pediatric studies, the frequency of domains and tests applied, showed a preponderance of attention/executive function investigations (Supplementary Tables S2, S3) with the majority being in 15-year-olds. That is to say, all subdomains were adversely affected by sleep restriction (i.e., especially inhibition, reaction time and accuracy). More recently, Short et al. [63], including 19 studies within the age range of 6- to 13-year-olds, concluded a medium meta-correlation only for the relationship between objective sleep duration and full intelligence quotient (IQ)/verbal IQ. No significant meta-association could be reported for fluid IQ, memory, executive function, processing speed and attention when reviewing 10 cross-sectional studies and nine experimental studies, which primarily used actigraphy. The authors additionally showed that the baseline sleep duration of only four observational studies fell into the recommended 9–11 h sleep duration guideline by the National Sleep Foundation [1] and the American Academy of Sleep Medicine [2]. All of the lower boundaries from the observational studies fell well below this 9-h cut-off. While only five of the experimental studies had a baseline at or slightly above this 9-h cut-off. Furthermore, none of the long sleep durations or sleep extensions surpassed even a 10-h cut-off.

Systematic reviews

de Bruin et al. [55], reporting only pediatric studies (substantial overlap with Lowe et al. [56]), reviewed sleep restriction and extension outcomes in adolescents. When quantifying their review, the number of nights with sleep manipulation ranged from 1 to 10 (including studies investigating napping) and involved manipulations ranging from ‘no sleep’ to ‘ \pm 1-h shifts’ (including also +5-min shifts and napping shifts). Fifty percent of the studies were performed in a lab setting (39% at home and 11% a combination thereof). In terms of sleep manipulation, 59% applied sleep restriction whilst 17% applied sleep deprivation, 6% sleep extension, 6% a combination and 12% other (e.g., napping). Actigraphy was the most commonly used tool (50% of the studies), followed by polysomnography (28%), sleep log (11%), and a combination thereof (11%). Supplementary Fig. S3 representing a

quantification of this systematic review shows that all domains of cognitive functioning are affected by sleep manipulations. That is to say, sleep restriction primarily affected: for the attention domain, the psychomotor vigilances; for working memory, the phonological working memory processes; for learning memory, the learning processes; for memory consolidation, the memory delayed recall functions; for creative/abstract thinking domain, the higher abstract thinking functions. Similarly for sleep extension designs, affected: for attention domain are psychomotor vigilances and sustained attention processes; for working memory are phonological working memory processes; for learning memory domain are learning, memory delayed recall, memory immediate recall and phonological working memory; for executive function domain are cognitive flexibility. Briefly, many functions benefit from sleep extension. In the 17 cognitive studies reviewed by Shochat et al. [41] based on primarily self-reports by adolescents, similar findings have been suggested. On the contrary, methodological flaws in the experimental designs prevent more firm conclusions. In Supplementary Table S4, we summarize potential study weaknesses specific to experimental designs investigating sleep manipulations.

A systematic review of non-experimental sleep manipulation studies, such as by delayed school start times [60], indicated reduced daytime sleepiness, depression, caffeine use, tardiness to class, and trouble staying awake.

Becker et al. [61] reported inconsistent results when investigating primarily the impact of intra-individual sleep variability. That is, differences exist in the domain affected (e.g., verbal, visuo-constructive/spatial abilities, intellectual functioning, sustained attention, P3 latencies) and in relation to the time of day with respect to the performance. Whereas the only study investigating school grades showed no association. Interestingly, the authors consider the intra-individual variability in sleep/wake patterns as characteristic of child and adolescent sleep. Such a perspective may partially explain the contradicting conclusions [13,54] regarding the truly beneficial role of sleep in the development of young children. That is, higher nighttime sleep proportions, and to a lesser extent also better sleep efficiency in infancy [54], was associated with improved executive functioning, reasoning, problem-solving skills; whereas performance after napping was reported to be improved (e.g., abstraction of grammatical relations, memory consolidation). Few objective sleep studies in preschoolers [62] were

found, though especially nighttime sleep duration associated positively with chiefly receptive vocabulary. Yet, others [13] are more critical towards the applied methodologies in these studies. Hence, a clear need for more systematic studies using stronger designs can be inferred.

Sensorimotor development

No reviews or meta-analyses were found.

Socio-emotional development

Because socio-emotional and behavioral development show significant overlap in applied tools, for instance as in the child behavior checklist, we consequently meta-analyzed their aESs together. Their d based on 11 aESs was 0.38 (95% CI: 0.28–0.49; z -value=7.3, $p<0.00001$; $I^2=86.9\%$, 95% PI: 0.8–75.1%).

Meta-analysis

Only Augustinavicius et al. [18] meta-analyzed polysomnographic features. For early-onset depression, they reported that the most robust finding was the longer sleep onset latency in childhood. Their results are furthermore in equivalence with sleep ontogeny, showing that age was a significant predictor of sleep micro-architecture. That is, reporting weak associations in early childhood but specifically for early depression-onset, a tendency for poorer coherence between beta/delta/theta across the hemispheres in this population. A more on-trend topic, and potentially not unrelated, is meta-analyzed by van Geel et al. [64], showing a medium association between victimization and sleeping problems.

Systematic reviews

More aggression and antisocial behaviors in evening types across childhood were systematically put forward by Schlarb et al. [65]. Whereas poor sleep perceived as a sleep disorder such as bruxism was significantly associated with psychosocial factors (e.g., emotional stress, higher

arousal index, and chiefly externalizing behavioral problems) in children older than 6 years [66]. Shochat et al. [41], focusing on adolescents, demonstrated the association between (primarily self-reported) poor sleep (six sleep duration, seven sleep problems, one tiredness, six insomnia, two sleep patterns, one sleep quality, one bedtime, one sleepiness, one sleep need) and a plethora of psychosocial health outcomes. Again, weak associations were concluded, but they remain suggestive of poorer psychosocial functioning such as in terms of anxiety, low self-esteem, depression, conduct problems or an adversely affected mental health status.

Becker et al. [61] reported mixed findings when describing the association between intra-individual sleep variability and emotional functioning, such as anxiety, depression, social problems, and behavioral reactivity. Of potential importance in these relationships are familial, cultural and environmental factors that may 'cause', 'moderate', 'modulate' or overall 'confound' our understanding of the true impact of poor sleep on socio-emotional functioning. Yet, glancing at the tabulated correlations, beta's, means or proportions, only small to moderate relationships have been revealed. Although Reynaud et al. [62] did not tabulate the size of the associations, when quantifying their review: (1) for externalizing behavior (aggressiveness, anger, attention problems, conduct problems, hyperactivity, impulsivity, opposition, and non-specific externalizing behaviors), 11 inverse associations were found with nighttime sleep duration, and positive associations for (2×) insomnia, (10×) nightwakenings, (4×) sleep onset latency, (8×) sleep period, (3×) bedtime, (1×) wake-up time but none with total sleep time and sleep efficiency; (2) for internalizing problems: one inverse association was found with total and nighttime sleep duration, and positive associations for (6×) nightwakenings, (2×) sleep onset latency, (3×) sleep period, (2×) bedtime. Sociability gave another associative profile, with mixed results for night wakenings, sleep onset latency, sleep period and wake-up time, and one negative association with bedtime.

Behavioral development

Systematic reviews and one meta-analysis

In the literature, systematic reviews have been primarily carried out for behavioral performance. Our following list of potential (and maybe overlooked) risk behaviors is food for thought. Shochat et al. [41] systematically reviewed 23 studies reporting risk behaviors (23 self-reports and two interviews) in 10- to 19-year-olds in association with sleep (10 sleep duration, four insomnia, eight sleep problems, seven sleep patterns, one sleep quality, one sleepiness, one tiredness). Under risk behaviors fall: smoking, drinking and driving, safety violations, delinquency, violence, suicide, illicit drug use, sexual activities, truancy, unintentional injuries, aggressive behavior. The authors ascribed the weaker relationships found in literature to the (co)occurrence/morbidity of emotional status, psychosocial functioning and adolescent-like life events.

Potentially due to such adolescent developmental salience, two studies addressed the school starting time debate in this age-range. A systematic review of delayed school start times, such as by 25–60 min, corresponded to a total sleep time increase of approximately 1 h [60] with concomitant reports of improved behavior (see Cognitive development) [60,67].

In preschoolers, non-specific behavior problems showed, albeit small but positive associations with nightwaking, sleep onset latency, sleep period, and to lesser extent, bedtime and wake-up time, and an inverse association with total sleep duration [62]. Moreover, intra-variability of sleep across childhood was related to poorer adjustment and greater risky behaviors [61].

A posteriori meta-analysis by sleep categorizations

When the aESs were categorized in terms of sleep, we found an overall moderate impact. The aggregated d based on 18 aES for sleep disorder were 0.39 (95% CI: 0.24–0.54; z -value=5.0, $p<0.00001$; $I^2=98.2%$, 95% CI: 0–100%), for sleep duration were 0.29 (11 aESs, 95% CI: 0.24–0.35; z -value=10.7, $p<0.00001$; $I^2=85.4%$, 95% PI: 10.6–47.8%), for sleep ‘in general’ were 0.31 (10 aESs, 95% CI: 0.21–0.41; z -value=5.8, $p<0.00001$; $I^2=93.1%$, 95% PI: 0–67%).

DISCUSSION

Based on 42 literature reviews (or 1117 studies) published during the past 5 years, we may conclude that poor sleep is moderately affecting performance and health during childhood. Although

more designs that are rigorous are needed, several main conclusions can be drawn based on the current available data. First, the impact of poor sleep can no longer be disregarded, neither by science nor society as quantified by our meta-analyses. Second, a vast amount of knowledge is generated by subjective measures, in particular of sleep. Third, the scientific literature is dominated by a health-scope. Consequently, insufficient understanding of the role of sleep particularly in childhood neurodevelopment (beyond health) can be inferred. To date, findings with respect to child neurodevelopment remain scattered, mixed and heterogeneous. This meta-analytic review therefore demonstrates a clear need for robust methodologies and replication studies, as well as naturalistic data collection.

Healthy development

A big boom in studies investigating sleep in relation to weight have been noticed in the past years [68–71]. Without going into much detail, mostly negative linear associations have been proposed with short sleep [72,73]; that is, with a lesser amount of sleep more likely being associated with be(com)ing overweight to obese. However, a large proportion of ‘short’ sleepers are not obese, and as a large proportion of ‘long’ sleepers are obese [74]. Studies have also controlled for a multitude of diverse confounders and covariates (e.g., parental weight, gender, sedentary lifestyle), and not in the least studies varied in the operationalization of weight and sleep, i.e. the cut-offs and measures [68]. Therefore, this meta-analytic review demonstrates that sleep is associated with weight, in spite of the ongoing discussion regarding the type of relationship and the ‘best’ methodology.

When we broaden our health scope, we may touch upon the literature with regard to SDB in particular. Whilst relationships between SDB, weight problems and cognitive abilities in pairs have been well-documented in the literature [41,75,76], the obesity epidemic gave rise to a more intricate discussion. Spruyt et al. [68, 77,78] showed that each might play a (mediator) role, and therefore the need for a more holistic perspective when investigating a health problem in childhood arises. Also, this meta-analytic review showed the role of poor sleep towards unhealthy development with a probable upcoming epidemic in childhood: sedentarism. Nevertheless, studies need to keep in mind

the directionality of relationships. Co-morbidities and/or co-occurrences were similarly not clear in reviewed sleep disorders such as bruxism, narcolepsy and restless legs syndrome.

Cognitive development

A keen interest in cognition was seen given that seven reviews, of which three were meta-analyses, have been published in the last 5 years. Findings concur with several older reviews on the association between primarily sleep duration and cognitive performance across childhood. For instance, Astill et al.[79] reported weak but significant meta-correlations for cognition, executive function, multiple-domain cognition and school performance with sleep duration. The authors failed to find a meta-association between sleep duration and sustained attention, explicit and implicit memory as well as intelligence upon investigating 86 studies within the age range of 5-12 years. The authors could neither conclude a meta-association with sleep efficiency, nor was the performance linked to an optimal sleep duration. Dewald et al. [80] is the only one who reported a small effect size with sleepiness. Despite the small effect sizes, and largely inconsistent findings, our findings equally suggest that during childhood the role of sleep in cognitive development cannot be ignored. In particular, executive functioning, reasoning and problem-solving abilities appear to be sensitive to poor sleep.

It remains a critical note that reported associations in the scientific literature have been vastly generated from ‘baseline sleep’[59] that repeatedly falls under the recommended sleep durations [1,2], or depends on sleep ranges that do not overlap with guidelines [1,2]. This should be a critical reflection when designing sleep manipulation studies. Furthermore, given the reported weaknesses in current experimental designs, which primarily focus on attention and/or executive function, the interrelation of the sleep–wake state and the multidimensionality of the concept ‘sleep’ should not be ignored. Of course, a publication bias can be expected. Hence, an attitude towards a more comprehensive investigation of sleep in its entirety is advocated.

Sensorimotor development

Copes et al. [81] reported as early as 1972 that sleep deprivation has an impact upon motor performance in children. For the sensorimotor domain, the publication by Walker et al. [82] in young adults has likely been pivotal, popularly concluding that practice with sleep makes perfect when subjects were tested on a sequential finger-tapping task. In addition, his study indicated the importance of the amount of stage N2. Yet, we need to remain critical that this is a motor skill ‘learning’ task. More recently, studies focusing on the sensorimotor development across childhood have been noticed. For instance, one [83] showed that when children had the opportunity to nap, they exhibited more efficient problem solving in a motor task; i.e. returning to walking after crawling through a tunnel for newly walking infants. Or briefly, a study [84] while unable to demonstrate any circadian association with motor skill acquisition, emphasized that especially the youngest group benefited the most from any sleeping opportunity (i.e. nap, nighttime sleep).

In developmental psychology, it is further well-acknowledged that sensorimotor development is critical in fostering the abilities to explore and to interact with the environment. Optimal integration of sensory information with coordinated motor movements gives rise to fundamental milestones, important for other developmental domains (e.g., socio-emotional).

Socio-emotional development

High odds ratios for socio-emotional problems given poor sleep in infancy have been reported [85], despite the small number of subjects falling in the clinical range (4.6%). Key players were sleeping less than 11 h, were experiencing more than 3 awakenings, a sleep onset latency of more than 30 min and a parental report of problematic sleeping. The systematic reviews reported in this paper testify this challenge in operationalizing poor sleep, and hence an inconsistency in this developmental association is concluded. Alternatively, few objective measurements of socio-emotional functioning have been applied.

Regarding socio-emotional development, we furthermore showed the importance of reflecting on results from a sleep–wake perspective. Previously we found that, in agreement with the eye-tracking literature, preferences for pleasant stimuli or happy faces and in particular preference for the

eye area by infants [86]. Upon including sleep parameters, findings showed that infants that had more sleep and less intra-daily variability as a (circadian) parameter had significantly better processing of the unpleasant stimuli and, to the same extent, of the neutral stimuli. But studies do not always need to be ‘high tech’, as shown by Sano et al. [87]. When repeatedly asking via visual analog scales the mood of college students, they showed that sleep regularity is a more important discriminator in predicting mood. Similar results have been confirmed based on facial muscle movement [88] or another study showing that a strong association between performance (decision-making) and self-regulation is moderated by sleep (baseline versus no napping conditions) [89]. In addition, we showed that the chronicity of poor sleep is another important determinant for socio-emotional signs to become of clinical significance [90]. Henceforward, a more comprehensive operationalization of the concept of (poor) sleep may expose the inconsistencies reported in literature.

The only meta-analysis of polysomnographic features in early-childhood-onset depression similarly denoted the challenge in operationalizing poor sleep and the importance of investigating the interrelation of sleep with developmentally salient characteristics. For instance, topographic differences in the two processes of sleep regulation (i.e. homeostatic and circadian) may elucidate neurodevelopmental vulnerabilities [22].

Behavioral development

Previously, we showed clearly the hand-in-hand association between the socio-emotional and behavioral performance with sleep, and the importance of investigating associations in terms of changes within the individual; i.e. individual sleep needs [90]. More specifically, sleeping more in the short term, but showing decreasing sleep duration in the longer term, was associated with clinically significant negative changes in adaptive skills. However, a continued decrease in sleep was associated with more behaviors warranting professional help. Per Shochat et al. [41], adolescents show risky behaviors and psychosocial problems, in particular with inadequate sleep durations. Shifts in school start times concur with improved ‘behavior’ per the systematic reviews included in this paper. Another supportive conclusion of this adverse association is based on the systematic review of intra-variability of sleep across childhood.

Thus, for socio-emotional and behavioral development, we can infer that poor sleep can negatively influence emotion/behavior at various stages of the regulatory process, being identification, selection and implementation of strategies, potentially leading to poor social interaction.

Lastly, whichever way we group the aESs, a moderate association between poor sleep and performance and health remains. This is suggestive of a robust association despite the current methodologies reported in scientific literature.

CONCLUSION

This meta-review highlights moderate and diverse associations between poor sleep and neurodevelopment of a child. First, it shows that current associations are based on few sleep manipulation studies, which fall on the extreme lower end of recommended hours of sleep during childhood. In addition, while the habitual sleep duration studies may suggest a slightly larger association, the reported sleep durations remain at the floor levels or lower levels of the guidelines. Second, very few studies conceptualized sleep in its entirety. Not only the circadian (mis)alignment, but especially the ‘forbidden zone’/time on task effect on performance has been consistently ignored when linking sleep to daytime performance across childhood. Lastly, sleep fluctuations in childhood might be a biological need and/or ecological opportunity, which necessitates a more comprehensive investigation of sleep to further improve our scientific and clinical work.

Conflict of interest

The author has no conflicts of interest to disclose.

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Supplementary material

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Figures and Tables

Fig. 1. Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flowchart.

Table 1. Descriptives of the papers included

Fig. 1.

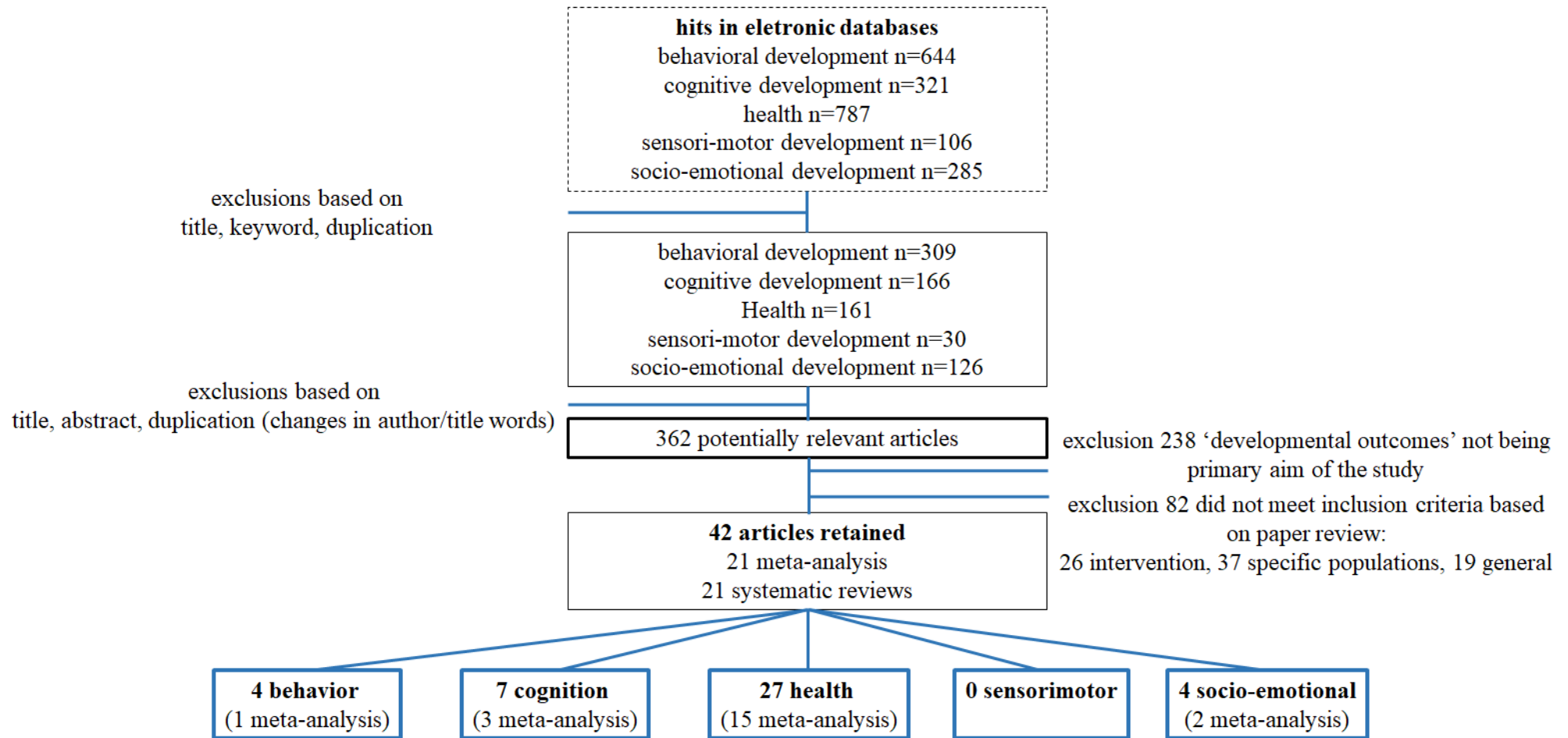


Table 1. Descriptives of the 42 papers included.

Author	Year	Country	Guideline	Search engines	Years searched	No. of Studies retrieved*	No. of studies selected	Systematic review/meta-analysis
Tonetti et al. [57]	2015	Italy	PRISMA	Scopus Web of Science	Without any restriction	1647	31	Meta-analysis
Lowe et al. [56]	2017	Canada	Cochrane Collaboration	PubMed, Scopus, Web of Science, PsycInfo		1145	61 (17 pediatric)	Meta-analysis
Short et al. [63]	2018	Australia		(EBSCOhost (CINAHL), Ovid (Medline, Embase, PsycArticles, PsycInfo), Cochrane, Web of Science, Scopus, Informit Health Database, PubMed	To December 2016	21747	19	Meta-analysis
de Bruin et al. [55]	2017	Netherlands		PubMed, PsychInfo	1981–2015	5581	16	Systematic review
Becker et al. [61]	2017	USA	PRISMA	CINAHL, Embase, PsycINFO, PubMed, Scopus	Between 2000 and 2015	1397	52	Systematic review
Tham et al. [54]	2017	Singapore		MEDLINE, Embase, Cochrane Library databases	January 2005 to December 2015	262	10 on cognitive development +20 on growth	Narrative review
Reynaud et al. [62]	2017	France	Cochrane Handbook, PRISMA	Medline, Web of Science, PsycINFO and ERIC	Up to 30 April 2016	3291	26	Systematic review
Shochat et al. [41]	2014	Israel		PubMed and PsycNET (PsycARTICLES PsycINFO)	Up to December 2012	898	76	Systematic review
Minges et al. [60]	2016	USA	PRISMA	Ovid Embase, Ovid MEDLINE, Ovid PsycINFO,		1029	Six studies : pre-post, no control	Systematic review

				Web of Science, Global Health, CINAHL			(n=3), randomized controlled trial (n=2), and quasi-experimental (n=1) designs	
Bowers et al. [67]	2017	USA		PsycINFO, PubMed, Scopus, ProQuest	In September 2016 and updated in March 2017	163	20	Meta-analysis
Guo et al. [50]	2017	China	PRISMA, Cochrane Handbook for Systematic Reviews of Interventions	PubMed, Excerpta Medica Database (Embase), Cochrane Library database, Web of Science, Chinese National Knowledge Infrastructure (CNKI), Chinese Biomedical Literature Database (CBM), Wanfang Data (WF)	Last search updated on 15 September 2016; no restriction on language or publication years	5637	14	Systematic review
Beris et al. [51]	2018	Australia		MEDLINE and Embase databases	From 1960 through June 2017	212	20	Systematic reviews
Augustinavicius et al. [18]	2014	Canada	Meta-analysis of Observational Studies in Epidemiology guidelines	MEDLINE, PSYCINFO, Embase, PubMed	Up to 1 March 2013	953	24	Meta-analysis
Van Geel et al. [64]	2016	Netherlands		PsycINFO, MEDLINE, ERIC, Embase, LILACS		212	21	Meta-analysis
Schlarb et al.	2014	Germany	PRISMA	MEDLINE, Web of Science,		1497	13 (9 children)	Systematic

[65]				EBSCO, Ovid, PubMed, Google Scholar, PsycINDEX				review
de Luca Canto et al. [66]	2014	Brazil	PRISMA	Cochrane, Embase, MEDLINE, PubMed, Virtual Health Library (BVS – Database that include articles in Spanish and Portuguese from MEDLINE, LILACS, Wholis, BBO and AdoLec)	In the past 5 years; End search date was 6 June 2014 across all databases	1012	7	Systematic review
Fatima et al. [26]	2015	Australia		MEDLINE, Embase, PubMed, CINAHL	Until May 2014	2070	11 for meta-analysis and 22 for systematic review	Meta-analysis
Ruan et al. [30]	2015	China	MOOSE	PubMed, Embase, Google Scholar	Through May 2015	168	25 (32 independent cohorts)	Meta-analysis
Fatima et al. [27]	2016	Australia	MOOSE Meta-analysis statement for reporting systematic reviews and meta-analysis	PubMed, Embase, and MEDLINE	Published until November 2015	1761	18 (of which 9 in meta-analysis)	Meta-analysis
Li et al. [28]	2017	USA		PubMed, Embase and the Cochrane Library	Up to April 2015	1733	12	Meta-analysis
Quist et al. [29]	2016	Denmark		PubMed	Until 10 August 2015		75	Meta-analysis
Wu et al. [31]	2017	China		Medline, Cochrane Library, Embase and Science Citation Index databases	From January 1980 through January	5110	13	Meta-analysis

								2015
Miller et al. [32]	2018	UK		PubMed, Embase, Web of Science, Cochrane	Up to 25 September 2017	2569	42 (20 for overweight/obesity, 14 for BMI z-score, and 16 for BMI).	Meta-analysis
Sedky et al. [35]	2014	USA		PubMed/Medline, PsychInfo and Cochrane databases, Google Scholar	Through September 2012	48	20	Meta-analysis
Galland et al. [34]	2015	New Zealand	PRISMA	PubMed, Web of Science, CINAHL, PsycINFO	Up to 1 March 2015	488	16	Meta-analysis
Mietchen et al. [36]	2016	USA	PRISMA	PsychInfo, PubMed, hand search, Web of Science.	Up through December 2015	1717	14	Meta-analysis
Song et al. [33]	2016	USA	PRISMA	PubMed/MEDLINE, Scopus, Web of Science, Cochrane Library	Inception through 2 September 2015	206	19	Meta-analysis
Yu et al. [39]	2017	China		PubMed, Embase and Cochrane library		621	11	Meta-analysis
Lee et al. [38]	2016	Taiwan	PRISMA Meta-analysis of Observational Studies in Epidemiology group.	PubMed, MEDLINE, Embase, Cochrane Review	January 1997 to July 2014	1103	51	Meta-analysis
Ehsan et al. [37]	2017	USA	PRISMA	PubMed, CINAHL, Embase, Scopus	All indexed years	1701	25	Meta-analysis
Carter et al. [40]	2017	USA	PRISMA	British Education Index, NAHL, Cochrane Library, ERIC, International Biography of Social Sciences, Medline via	From 1 January 2011 to 15 June 2015	467	11	Meta-analysis

				Ovid (Embase, Medline, Psych INFO); PubMed, Science Direct, Scopus, Web of Science				
de Azevedo Abreu et al. [42]	2015	Brazil	PRISMA	Medline via PubMed, LILACS, Web of Science, Scopus, Adolec	August 2014	859	7	Systematic review
Chaput et al. [43]	2016	Canada	PRISMA	Ovid interface: MEDLINE (1946 to January 19, 2015), Embase (1980 to 2015 week 3), PsychINFO (1906 to 2015 week 3), and CINAHL (1961 to 2015 week 3)		5825	141	Systematic review
Chaput et al. [44]	2017	USA	PRISMA	MEDLINE, Embase, PscINFO and the Cochrane Central Register of Controlled Trials (CENTRAL)	No limits	1385	69	Systematic review
Felso et al. [45]	2017	Hungary		Ovid MEDLINE, Scopus and Cochrane Central Register of Controlled Trials (CENTRAL) databases	From inception until March 2016	3540	33	Systematic review
de Castro Corrêa [46]	2017	Brazil		LILACS, PubMed, Scopus, and Web of Science	2004 to 2014	122	6	Systematic review
da Silva Gusmao Cardoso et al. [47]	2018	Brazil		MEDLINE/PubMed, LILACS, SciELO, ISI Web of Science, PscINFO	From 2002 to 2016	649	34	Systematic review
Saunders et al. [48]	2016	Canada		MEDLINE, Embase, SPORTdiscus, CINAHL, PscINFO	Published in 2008 or later	489	14	Systematic review
Dolezal et al. [49]	2017	USA	PRISMA	PubMed and Google Scholar	Between January 2013 and	2122	34	Systematic review (including

					March 2017			meta-analyses and individual studies)
Blackwell et al. [52]	2017	UK	PRISMA	The Cochrane Library, Embase Ovid, MEDLINE PsycINFO	Between 2005 and 2015; on 28 August 2015	710	8	Systematic review
Angriman et al. [53]	2017	Italy	PRISMA	PubMed, Ovid (including PsycINFO, Ovid MEDLINE®, and Embase), Web of Knowledge (Web of Science, Biological abstracts, BIOSIS, FSTA)	November 2015	1185	42 (33 tabulated)	Systematic review
Thorpe et al. [13]	2015	Australia	PRISMA	MEDLINE (via Ebscohost), PsycINFO (via Ebscohost), CINAHL (via Ebscohost), Web of Science, Scopus, ERIC (via Ebscohost).		781	26	Systematic review

BMI, body mass index; MOOSE, Meta-analysis Of Observational Studies in Epidemiology; PRISMA, Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines.

* Some counts might still include duplicates.

SUPPLEMENTARY MATERIAL

Supplementary Fig. S1. Guidelines of sleep durations

Supplementary Fig. S2. The concept of poor sleep

Supplementary Fig. S3. Quantification of a systematic review on neuropsychological outcomes

Supplementary Table S1. Search terms of the reviews and meta-analyses included

Supplementary Table S2. Sleep and outcome measure as well as conclusions of the papers included

Supplementary Table S3. Measures applied in the papers included

Supplementary Table S4. Several weaknesses in experimental designs assessing sleep manipulations

Supplementary Table S1: Search terms of the reviews and meta-analyses included

Author	Search terms
Tonetti et al ⁵⁷	morningness OR eveningness OR circadian phase OR circadian typology OR circadian preference OR owl OR lark OR chronotype OR circadian rhythm OR diurnal preference OR sleep) AND (achievement OR performance) AND (school OR University OR academic)
Lowe et al ⁵⁶	sleep restriction, sleep manipulation, sleep fragmentation, partial sleep deprivation, or sleep loss + executive function, executive control, cognition, memory, cognitive, inhibitory control, response inhibition, set shifting, task shifting, task switching, mental flexibility, decision making, attentional control, attention, verbal fluency, psychomotor vigilance, intelligence, recall, response time, reaction time, delay discounting, event related potential
Short et al ⁶³	sleep duration (ie, using actigraphy or polysomnography [PSG]) and children’s cognitive function/(Children or Adolescen* or Youth or Young People or Pediatric or Paediatric) and (Sleep or Wake After Sleep Onset (WASO) or Sleep Onset Latency (SOL) or bed time / bedtime or wake time / waketime or sleep efficiency) and (Cognit* or Reaction Time or Attention or PVT or Psychomotor Performance or Memory or IQ or Intelligen* or Problemsolv* or Neuropsych*).
de Bruin et al ⁵⁵	'cognition', 'sleep', 'deprivation', and 'adolescence'; more details in their supplemental files
Becker et al ⁶¹	“actigraph*”, “diary”, “diaries”, “log(s)”, “daily”, “everyday”, “night*”, “day*”, “week*”, “month*” + “variability”, “variation”,“(in)stability”, “fluctuation”, “(ir)regularity”, “(ir)regular sleep*”,“(ir)regular bedtime”, “(ir)regular rise*”
Tham et al ⁵⁴	“sleep” AND “infant” AND “cognition” OR “memory” OR “executive functioning”, OR “growth” OR “obesity” OR “growth hormone” OR “stunting”, and combinations thereof.
Reynaud et al ⁶²	sleep, insomnia, night-waking, child, preschoolers, cognition, learning, teacher rating, performance, intelligence, IQ, memory, attention deficit, sustained attention, behavior, conduct, internalizing, externalizing.
Shochat et al ⁴¹	‘sleep’ (covering all aspects of interest regarding sleep, e.g.,: short sleep duration, sleep loss, sleep disturbances) and ‘insomnia’, ‘health’, ‘performance’, and ‘risk’, ‘adolescents’
Minges et al ⁶⁰	“Students” AND “Schools OR Education” AND “Sleep Deprivation OR Sleep OR Circadian Rhythm OR School Start Time OR Start Time OR Start Late OR Start Delay OR Start Stagger OR Start Early OR Eveningness OR Wakefulness”
Bowers et al ⁶⁷	school start time, students, school, education, sleep, sleep deprivation, sleep restriction, circadian rhythm, adolescent, and sleep pattern
Guo et al ⁵⁰	Bruxism[Mesh] OR Sleep Bruxism[Mesh] OR Teeth Grinding Disorder[Title/Abstract]) OR Teeth Grinding Disorders[Title/Abstract] OR Sleep Bruxisms[Title/Abstract] OR Nocturnal Teeth Grinding Disorder[Title/Abstract] OR Nocturnal Bruxism[Title/Abstract] OR Nocturnal Bruxisms[Title/Abstract] OR Childhood Sleep Bruxism[Title/Abstract] OR Childhood Sleep Bruxisms[Title/Abstract] OR Sleep-Related Bruxism[Title/Abstract] OR Sleep-Related Bruxism[Title/Abstract] OR Adult Sleep Bruxism[Title/Abstract] OR Adult Sleep Bruxism[Title/Abstract] OR bruxism[Title/Abstract] OR teeth grinding[Title/Abstract] OR Sleep bruxism[Title/Abstract]) AND (children[Title/Abstract] OR child[Title/Abstract] OR kid[Title/Abstract] OR

	kids[Title/Abstract] OR Child[Mesh])
Beris et al ⁵¹	narcolepsy OR idiopathic hypersomnia, AND children OR pediatric OR paediatric, AND cognition OR memory OR learning OR cognitive OR neuropsychological OR neurobehavioural OR neurobehavioral OR behaviour OR behavior.
Augustinavicius et al ¹⁸	major depressive disorder OR depression OR MDD AND children OR adolescents OR teenagers OR youth AND polysomnograph OR polysomnography OR PSG OR REM OR slow wavesleep OR slow waveactivity OR NREM sleep OR delta sleep OR sleep macron OR sleep macroarchitecture OR sleep micron OR sleep microarchitecture OR coherence OR temporal coherence
van Geel et al ⁶⁴	not reported
Schlarb et al ⁶⁵	chronotype, chronobiology, morningness, eveningness, owls and larks as well as diurnal preference to fully capture every aspect of chronotype; aggression, anger, hostility, violence, anti-social behavior, conduct disorder, oppositional defiant disorder, delinquency, social adjustment and externalizing behavior
de Luca Canto et al ⁶⁶	Database search is online available (but could be retrieved)
Fatima et al ²⁶	not reported
Ruan et al ³⁰	“sleep” and “obesity”, “adiposity”, “body mass index”, “body weight”, “waist circumference”, or “skinfold thickness”, and “follow-up studies”, “longitudinal studies”, or “prospective studies” and “children” or “adolescents”.
Fatima et al ²⁷	sleep problems, sleep disturbances, poor quality, poor efficiency, or longer latency and overweight, obesity
Li et al ²⁸	‘sleep duration’ and ‘body mass index’, or ‘BMI’, or ‘obese’, or ‘obesity’, or ‘weight’, or ‘overweight’, or ‘adipose’, or ‘adiposity’.
Quist et al ²⁹	“children”, “adolescents”, “sleep”, “cardiometabolic”, “metabolic health”, “abdominal obesity”, “glucose”, “insulin”, “lipids”, “dyslipidemia”, “triglycerides”, “cholesterol”, “blood pressure”, “hypertension”, and “inflammation”
Wu et al ³¹	“sleep” and “obesity” or “overweight” or “weight” and “prospective” or “cohort” or “longitudinal” or “observational”
Miller et al ³²	“Sleep terms” (sleep OR sleep-disordered breathing OR bed time) in combination with “Obesity terms” (BMI OR body mass index OR weight OR waist circumference OR waist OR WHR OR waist hip ratio OR obese OR overweight OR adiposity OR adipose tissue OR anthropometry OR body composition OR body constitution) and “Study Population terms” (children OR adolescents OR pediatrics OR pediatric OR paediatric OR paediatrics OR infant OR preschool) with “Study type terms” (prospective OR cohort OR longitudinal).
Sedky et al ³⁵	“attention deficit hyperactivity disorder” or “ADHD” and “obstructive sleep apnea” or “OSA” or “sleep disordered breathing” (SDB) or “SDB”
Galland et al ³⁴	Search (child, OR adolescent) AND (sleep disordered breathing OR, obstructive sleep apnea, OR snoring) AND (academic performance, OR educational achievement, OR academic achievement, OR school performance, OR learning, OR school problems) Filters: Humans; Child: 6–12 years; Adolescent: 13–18 years
Mietchen et al ³⁶	pediatric SDB and executive function using the search terms “(apnea OR sleep disordered breathing) AND (pediatrics OR children OR adolescents) AND (executive function OR cognition OR memory OR neurocognitive OR neurobehavioral OR executive dysfunction OR dysfunction)”

Song et al ³³	“adenotonsillectomy,” “tonsillectomy,” “neurocognitive,” “neuro*,” “cognition,” “snoring,” “sleep apnea,” “sleep disordered breathing,” “surgical,” “surgery,” “sleep apnea syndrome,” and “obstructive sleep apnea.
Yu et al ³⁹	cognitive measures were “neurocognitive deficit”, “cognition”, “cognitive ability”, “mental status schedule”, “neuropsychology”, “memory”, “attention”, “arousal”, “executive function”, “sleep disordered breathing” and “sleep apnea syndromes” adenotonsillectomy”, “adenoidectomy”, and “tonsillectomy”
Lee et al ³⁸	sleep apnea, OSA, sleep apnea syndromes, tonsillectomy, adenoidectomy, infant, child, adolescent, and Humans.
Ehsan et al ³⁷	("Blood Vessels"[mesh]) OR "Hypotension"[mesh]) OR "pulse"[mesh]) OR "Coronary Artery Disease"[mesh]) OR "Arrhythmias, Cardiac"[mesh]) OR "Stroke"[mesh]) OR "Hemodynamics"[mesh]) OR "Electrocardiography"[mesh]) OR "Atrial Function"[mesh]) OR "Heart Failure"[mesh]) OR "Nitric Oxide"[mesh]) OR "Hypertension, Pulmonary"[mesh]) OR (((("Baroreflex"[mesh]) OR ("Pressoreceptors"[mesh]) OR Baroreceptor)))) OR "Chemoreceptor Cells"[mesh]) OR "Natriuretic Peptides"[mesh]) OR "Cardiac Output"[Mesh]) OR "Heart Rate"[Mesh]) OR "Echocardiography"[Mesh]) OR (((("Ventricular Dysfunction"[Mesh] OR "Ventricular Dysfunction, Right"[Mesh] OR "Ventricular Dysfunction, Left"[Mesh]))) OR "Ventricular Remodeling"[Mesh]) OR "Hypertension"[Mesh]) OR "Endothelium"[Mesh]) OR "Atherosclerosis"[Mesh]) OR (((("Autonomic Nervous System Diseases"[Mesh]) OR "Autonomic Nervous System"[Mesh]))) OR "Blood Pressure"[Mesh]) OR "Cardiovascular System"[Mesh])) AND "Sleep Apnea Syndromes"[Mesh])) AND (((("Child"[Mesh]) OR "Adolescent"[Mesh]))) AND english[Language])) AND ("Longitudinal Studies"[Mesh] OR "Prospective Studies"[Mesh] OR "Follow-Up Studies"[Mesh] OR "Long-term"[All Fields] OR "long term"[All Fields] OR "Epidemiologic Study Characteristics as Topic"[Mesh] OR "Clinical Trial" [Publication Type]) NOT "Cross-Sectional Studies"[mesh]
Carter et al ⁴⁰	not reported
de Azevedo Abreu et al ⁴²	sleep (sleep); the second with terms related to adolescence (adoles*, teen*, student*, youth, young); and the third with terms related to lipids (lipid*, lipemia*, cholesterol, HDL, LDL, triglyceride*, lipoprotein*, hypercholesterolemia*, hypercholesteremia*, dyslipidemia*, dyslipoproteinemia*, hyperlipidemia*, hyperlipemia*, “high density lipoprotein cholesterol”, “low density lipoprotein cholesterol”)
Chaput et al ⁴³	not reported
Chaput et al ⁴⁴	not reported
Felso et al ⁴⁵	obesity] AND [terms for sleep] AND [terms for children or adolescence]
de Castro Corrêa ⁴⁶	“Child Language” AND “Obstructive Sleep Apnea”, as well as their counter-parts in Portuguese, “Linguagem Infantil” AND “Apneia do Sono Tipo Obstrutiva”
da Silva Gusmao Cardoso et al	Apneia do Sono Tipo Obstrutiva, Sleep Apnea, Obstructive and Apnea del Sueño Obstrutiva; Neuropsicología, Neuropsychology and Neuropsicología; Cognición, Cognition and Cognición; Atención, Attention and Atención; Memoria, Memory and Memoria; Funciones ejecutivas, Executive functions and funciones ejecutivas; Linguagem, Language and Lenguaje; Aprendizagem, Learning and Aprendizaje; Baixo Rendimento Escolar, Underachievement and Rendimiento Escolar Bajo; Comportamento, Behavior and Conducta.

Saunders et al ⁴⁸	(health* OR wellness OR well being OR wellbeing OR “quality of life” OR social behav* OR prosocial behav* OR behavio* conduct or conduct disorder* OR aggression OR delinquen* OR academic achievement OR educational achievement OR grade point average OR GPA OR drop out OR dropout OR attention or concentrat* OR psychomotor performance OR motor development OR motor skill* OR motor activit* OR movement OR physical competenc* OR physical* litera* OR postural balance OR depression OR depressive OR depressed OR mood disorder* or anxiety OR distress OR worry OR burnout OR burn out OR psycho-social adjustment or psychosocial adjustment OR self esteem OR self concept OR (bone N2 density) OR (bone N2 mass) OR hypertens* OR high blood pressure OR cholesterol OR hypercholester* OR hyperlipid* OR dyslipid* OR lipids* OR lipoprotie* OR obese OR obesity OR overweight OR body mass index OR BMI OR waist OR adipos* OR fat OR metabolic syndrome OR insulin resistance OR diabet* OR glucose OR HBA1C OR fitness or physical condition*) AND (physiological monitor* OR DE "Patient Monitoring" OR DE "Patient Self-monitoring" OR (objective* N3 measur*) OR (direct* N3 measur*) OR activPAL* OR ActiGraph* OR acceleromet* OR heartrate monit* OR heart rate monit* OR pedomet* OR armband* OR arm band* OR inclinomet or activity monitor* OR activity tracker* OR fitness tracker* OR portable monitor* OR wearable monitor* OR Fitbit* OR Vivofit* OR Fuelband* OR Actical OR Genea) AND (boy OR boys OR girl* OR child* OR schoolchild* OR adolescen* OR juvenil* OR youth* OR teen* OR pubescen* OR pediatric* OR paediatric*)
Dolezal et al ⁴⁹	“sleep,” “exercise,” “regulation,” “loss,” “aerobic,” “heart rate variability,” “resistance,” “deprivation,” and “performance”
Blackwell et al ⁵²	(Narcolepsy OR Cataplexy) AND (Children OR Adolescents) AND Cognition OR Psychosocial Well-Being.
Angriman et al ⁵³	Restless legs syndrome, anxiety, attention-deficit/hyperactivity disorder (ADHD) and related neurodevelopmental conditions, cardiovascular diseases, depression, diabetes, kidney disease, fibromyalgia, insomnia, liver/gastrointestinal disease, migraine, narcolepsy obesity, polyneuropathy, rheumatological disorders (including rheumatoid arthritis) and somatoform pain disorder
Thorpe et al ¹³	(“daytime sleep” OR nap* OR “day?sleep” OR “sleep consolidation”) AND (cognition OR behavio?r OR “physical Health” OR “night sleep”) AND (child*OR infant OR bab*)

Supplementary Table S2: Sleep and Outcome measure as well as conclusions of the papers included

Author	Sample size	Age-ranges	Moderator/grouping variables	Sleep	Outcome
Tonetti et al ⁵⁷	27 309		school versus university pupils GPA measure	6 Composite Scale of Morningness; 8 Morningness–Eveningness Questionnaire; 7 Morningness–Eveningness Scale for Children; 2 adaptation for pupils of the Morningness–Eveningness Questionnaire; 3 Munich Chronotype Questionnaire; 2 Lark-Owl Chronotype Indicator	GPA (18 self-reports and 12 objective measures)
	Conclusion	higher effect size in school pupils (g: 0.166, 95%CI: 0.127 to 0.206) compared to university students (g: 0.121, 95%CI: 0.080 to 0.163). Note: no age in years effect. Self-report measures of grades revealed a stronger effect size (g:0.171; 95%CI: 0.137 to 0.206; N=20); compared to objective measures (g:0.093; CI: 0.047 to 0.140; N=19)			
Lowe et al ⁵⁶	1688; pediatric sample sizes ranged from 6 to 82 and the average age-ranges investigated was 3.8 to 18.9	3 to 60+	age group, time of day, cumulative days of restricted sleep, sleep latency, subjective sleepiness, gender	experimentally manipulated sleep restriction	cognitive domains: 10x for the attention domain (including 6x sustained attention with primarily the Psychomotor Vigilance test), 8x for the executive function domain (including 2x assessing inhibition,

3x working memory,
 3x complex
 functioning with
 primarily the N back
 and digit span test),
 2x for the impulsive
 decision making
 domain and 6x for the
 memory domain with
 primarily verbal
 functions

Conclusion cognitive performance (g: -0.383, p<0.001); reaction time (RT) and accuracy, reduced sustained attention (g:-0.409, p<0.001); RT and lapses, executive dysfunction (g:-0.324, p<0.001), RT and accuracy and multitasking (g:-0.294, p<0.001) Note: deficits in attention accuracy was affected (g:-0.061, p=0.006). All moderators were significant

Short et al⁶³ varied from 6 to 828 mean ages ranging from 6.8 to 12.5 years compared to NSF and AASM recommendations sleep time was defined as total nocturnal sleep duration as measured by actigraphy or PSG. full IQ/verbal IQ fluid IQ memory executive function processing speed attention

Conclusion effect sizes were non-significant for all cognitive domains, with the exception of full/verbal IQ

de Bruin et al⁵⁵ sample sizes ranging from 6-82 subjects age-range of 8.6 to 20 years the effects of sleep restriction or deprivation forty-five cognitive tests were reported assessing different aspects of cognition; five cognitive domains, including their sub-domains: attention (including selective, divided and sustained attention), working memory (including

visuospatial and phonological working memory), declarative memory (including learning, immediate and delayed recall), executive functions (including cognitive flexibility and cognitive control/inhibition), and creative and abstract thinking (including reasoning)

Conclusion

the largest effects are found in sleep deprivation studies with decrements in the vigilance tasks such as the PVT as most consistent finding; sleep extension in adolescents with chronic sleep reduction and sleep improvement in adolescents with insomnia contribute to improvement in working memory; sleep directly after learning improves memory consolidation; generally, the sleep restriction studies show absent or small effects on cognitive functioning

Becker et al ⁶¹	between 10 to 761	≤18 y old	age, gender, ethnicity, maternal	mean sleep variables, intra-individual variability of sleep/wake patterns from daily sleep using actigraphy and sleep diaries	<u>development:</u> age, pubertal status; <u>family, cultural, and environmental factors:</u> race/ethnicity, socioeconomic status, family structure and functioning, sleep environment, time spent on activities, community factors; <u>physical factors and health:</u> Sex, BMI obesity, nutrition, other; <u>psychosocial, emotional, and</u>
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behavioral functioning:
 emotional functioning, behavioral functioning, social functioning.
cognition and learning: specific neurocognitive functions, academics;
neurodevelopmental disorders: ADHD, Autism and other developmental disabilities e.g. Fragile X syndrome;
Sleep functioning: mean sleep variables, intellectual ability sleep schedule, habits, and problems , daytime sleepiness and napping , Snoring; sleep interventions

Conclusion

intra-individual variability in select aspects of sleep does appear to be associated with: increasing age/pubertal status, non-White race, physical and neurodevelopmental conditions (e.g., attention-deficit/hyperactivity disorder; autism), psychopathology symptoms (e.g., anxiety, depression, inattention), body weight, stress, aspects of cognitive functioning, and poorer sleep functioning/habits

Tham et al⁵⁴

6 months to 18 months

short term/long term

sleep log (n=6), actigraphy (n=6), questionnaire (n=2); 24hr sleep, nap, nighttime sleep

cognitive development

	Conclusion	positive association between sleep, memory, language, executive function, and overall cognitive development in typically developing infants and young children			
Reynaud et al ⁶²	58 - 8950	2 years and less than 6 years		over half of the articles on sleep duration, 13 on night sleep duration and 6 for total sleep duration, 8 on night-waking, 5 on sleep-onset latency, 2 sleep efficiency, 1 on insomnia, 6 on sleep problems, 3 on bedtime, 1 wake-up time; 11.5% objective measurement	23 on sleep and behavior, and 7 on sleep and cognition with a notable focus on language skills
	Conclusion	association between sleep, behavior and cognition as early as preschool years, but the strengths of associations reported in the articles were relatively small			
Shochat et al ⁴¹		ranging between ages 10-19 years, or the equivalent school grades (grades 5-12)		sleep duration/loss/deprivation, sleep disturbance and insomnia	1) somatic health, 2) psychosocial health, 3) academic/school performance 4) risk behaviors
	Conclusion	inadequate sleep is associated with negative outcomes in several areas of health and functioning, including somatic and psychosocial health, school performance and risk taking behavior			
Minges et al ⁶⁰	47 to 10,65	from 10.8 to 16.4 years	intervention vs control (3 pre-post, no control, 2 randomized controlled trial, and 1 quasi-experimental designs)	delayed school start time: sleep patterns, sleepiness, sleep duration	attention performance, academic achievement, motor vehicle crashes, mood, and health-related outcomes;
	Conclusion	<u>academic achievement</u> : pre: 93% post: 91% <u>tardiness</u> : pre: 25% post: 16% ; <u>presenteeism (sleepiness/falling asleep in class)</u> : pre: 72% post: 55%; <u>too tired to do schoolwork</u> : pre: 76% post: 61% ; <u>too tired to play sports</u> : pre: 45% post: 44% ; <u>too tired to socialize</u> : pre: 45% post: 38%; <u>too tired to play sports</u> : NS; <u>hours spent on homework</u> : NS ; <u>participation in school sports</u> : NS; <u>participation in organized community sports</u> : NS; <u>music activities</u> : NS; <u>volunteer</u>			

<u>work: NS; hanging out with friends: NS</u>					
Bowers et al ⁶⁷	15 to 10656	high school student samples	delay of school start time in minutes, before and after 8:30 AM school start time (American academy of Pediatrics guideline), student grade in school, time elapsed between assessments before versus after an school start time delay	school start time and sleep duration	daytime sleepiness, absences from school, and tardiness to school
	Conclusion	later starting school times are associated with longer sleep durations; later start times were associated with less daytime sleepiness (7 studies) and tardiness to school (3 studies) show by longitudinal and cross-sectional studies			
Guo et al ⁵⁰	10902	ages 0 to 12 years		sleep behaviors that serve as risk factors related to bruxism	sleep behavior
	Conclusion	the pooled ORs, 95% CIs, and P values were as follows: <u>snoring</u> (2.86, 1.85–4.42, <0.0001); <u>mouth breathing</u> (1.51, 1.04–2.18, 0.029); <u>restless sleep</u> (2.31, 1.89–2.83, <0.0001); <u>drooling</u> (1.79, 1.07–2.97, 0.026); <u>stomach position during sleep</u> (1.70, 1.0–2.39, 0.003); <u>inadequate sleep time</u> (2.56, 1.48–4.43, 0.001)			
Beris et al ⁵¹	926 narcoleptics, 18 idiopathic hypersomnolence			narcolepsy and idiopathic hypersomnia	overall performance
	Conclusion	there does not appear to be a clear association between intellectual functioning and narcolepsy or idiopathic hypersomnia; variability in results from studies investigating associations between academic achievement and these two hypersomnolence disorders; behavior and emotion appear to be significantly affected by narcolepsy; only two studies included populations of children and adolescents with idiopathic hypersomnia			
Augustinavicius et al ¹⁸	5 to 24	12 years or younger; adolescents were 13–21years	children and adolescents; age, major depressive disorder characteristics such as the number of previous major depressive episodes and episode length, and comorbid	sleep macro-and microarchitecture; intrahemispheric coherence between beta and delta in the right hemisphere	major depressive disorder

		psychiatric diagnoses on sleep macro-architecture	(BDRCOH), beta and delta in the left hemisphere (BDLCOH), theta and delta in the right hemisphere (TDRCOH), theta and delta in the left hemisphere (TDLCOH), and interhemispheric coherence of beta between the right and left hemispheres (BCOH), and theta between the right and left hemispheres (TCOH)	
	Conclusion	the most robust difference was found in sleep latency, 31% of adolescents with major depressive disorder had increased sleep latency; age, suicidal ideation, suicidal behavior, and psychiatric comorbidities were significant predictors of sleep macro-architecture; modest differences were found for sleep micro-architecture, intra-hemispheric and interhemispheric temporal coherence was decreased in a third of patients with major depressive disorder		
van Geel et al ⁶⁴	363539	age from 7 up to 19 y of age	sleep problems	peer victimization
	Conclusion	sleeping problems may be used as a possible signal that a child is victimized by peers		
Schlarb et al ⁶⁵	11 299	between 0 and 27 years	gender	chronotype
	Conclusion	behavioral and emotional problems as aggression or antisocial behavior were more pronounced in eveningness than in morningness-types		
de Luca Canto et al ⁶⁶	10-129	5 to 17	sleep bruxism	psychosocial factors: description of some temperamental traits that characterize bruxers: e.g., aggressiveness, hostility,

					perfectionism, and stress sensitivity
	Conclusion	no evidence supportive of an association between sleep bruxism and psychosocial factors in children younger than 5 years; association between sleep bruxism and psychological factors in children older than 6 years			
Fatima et al ²⁶	24821, with average 5-year follow-up	0 – 18 years	in/before/after 2008, <5 years, 5–10 years, ≤10 years, 10–19 years	longitudinal association between sleep; the definition of ‘short sleep duration’ in young children varied from sleep hours <12 h per night to <10 h per night, for older children it varied from sleep hours <7.5 h per night to <10.5 h per night and among adolescents it varied from sleep, 19 parental reports, 3 self-reports and 2 a combination	BMI
	Conclusion	revealed that subjects sleeping for short duration had twice the risk of being overweight/obese, compared with subjects sleeping for long duration (OR: 2.15; 95% confidence interval: 1.64–2.81)			
Ruan et al ³⁰	including 56 584 children and adolescents with average 3.4-year follow-up	0 – 16 years at baseline		habitual sleep duration	obesity
	Conclusion	sleep duration in children and/or adolescents is inversely associated with the risk of overweight/obesity in a dose-response manner			
Fatima et al ²⁷	26,553 subjects	0 – 34 years (4 studies are 18+)	age	inadequate sleep: 1. Inadequate sleep predominantly measured as insufficient duration, e.g., short duration of sleep. 2. Inadequate sleep predominantly measured as poor quality irrespective of	obesity

				sleep duration. These include problems associated with sleep initiation (e.g., higher latency) and maintenance (e.g., sleep disturbances, recurrent awakenings, poor efficiency) 3. Inadequate sleep as an overall measurement of sleep including both duration and quality, e.g., using the Pittsburgh Sleep Quality Index (PSQI)	
	Conclusion	inadequate sleep OR: 1.27 95% CI: 1.05-1.53); considerably higher odds (OR = 1.46, 95% CI: 1.24-1.72) in young subjects with poor sleep quality (independent of duration)			
Li et al ²⁸	44 200 children with 4.6 years follow up Conclusion	0 – 18 years	age, region, sample size, sleep period, years of follow-up, quality	sleep duration	obesity
		short sleep duration was significantly associated with obesity, the pooled results remained significant/unaltered association in the subgroup analysis			
Quist et al ²⁹	90-8444	3-20 y,	abdominal adiposity, glucose homeostasis, blood lipids, blood pressure, inflammation	sleep	cardiometabolic risk; 38 studies (n = 71,806) included measures of abdominal adiposity, 21 studies (n = 15,561) included measures of glucose homeostasis, 14 studies (n = 30,098) included measures of blood lipids, 30 studies (n = 62,146)

					included measures of blood pressure, and nine studies (n = 8,266) included measures of inflammatory markers
	Conclusion	an increasing number of observational studies suggests that adequate sleep (quantity as well as quality) in children and adolescents most likely contributes to a lower cardiometabolic risk			
Wu et al ³¹	35,540	0-18 years, with 6.5 years follow-up	duration follow up, study location, definition obesity/overweight, cut-off sleep duration, reclassified Sleep Health Foundation reference sleep	short sleep duration	obesity
	Conclusion	short sleep duration in children is associated with a significantly increased risk of obesity			
Miller et al ³²	overall, for sleep and obesity, the meta-analysis included 75 499 participants from nine different countries, for BMI 24 894 from nine countries, and for BMI z-score 31 665 from eight countries, prospective, had follow-up of ≥1 year (average 4.4 years)	0 to 12 years	age strata, by continent in the combined age groups	sleep duration	obesity
	Conclusion	infancy (7 studies, 14 738 participants, RR: 1.40; 95% CI 1.19 to 1.65; p < .001); early childhood (eight studies, 31 104 participants, RR: 1.57; 1.40 to 1.76; p < .001); middle childhood (three studies, 3 005 participants, RR: 2.23; 2.18 to 2.27; p < .001); and adolescence (three studies, 26 652 participants, RR: 1.30; 1.11 to 1.53; p < .002)			

Sedky et al ³⁵	1113 (874 diagnosed with SDB who were examined for ADHD symptoms; 239 diagnosed with ADHD who were examined for SDB) and 1405 in the control-group	0 to 18 years	pre- versus post-adenotonsillectomy	polysomnography was required to be done both before and 1e 13 months after adenotonsillectomy	ADHD
	Conclusion	ADHD symptoms are related to SDB and improve after adenotonsillectomy; a high apnea hypopnea index cutoff was associated with lower effect sizes, while child age, gender and body mass index did not moderate the relationship between SDB and ADHD			
Galland et al ³⁴	ranged from 66 to 6349	5 to 17		SDB	academic performance
	Conclusion	language arts (ES -0.31; P = .001; I2 = 74%), math (ES -0.33; P = .001; I2 = 55%), and science (ES -0.29; P = .001; I2 = 0%), with unsatisfactory progress/learning problems (ES -0.23; P = .001; I2 = 0%) but not general school performance			
Mietchen et al ³⁶	1697 children	ages 5 to 17 years	per executive domain, SDB severity	SDB severity: mild, moderate, severe.	five executive domains: vigilance, inhibition, working memory, shifting, generativity
	Conclusion	lower performance in generativity on objective neuropsychological measures; no differences associated with SDB severity; questionnaire data suggested dysfunction across the three executive domains measured : inhibition, working memory, shifting			
Song et al ³³	898	6.6 ± 2.3 years (range 2.5–14 years)	age	pediatric adenotonsillectomy for obstructive sleep apnea	neurocognitive outcomes
	Conclusion	decreased effectiveness in older children suggests possibly a threshold age when neurocognitive deficits become irreversible			
Yu et al ³⁹	ranged from 26 to 565	3.8-10.9	cognitive domains, pre versus post; healthy controls	sleep disordered breathing; adenotonsillectomy ranged from 6 to 12 months	4 cognitive domains: general intelligence, memory, attention-executive function

					and verbal ability
	Conclusion	SDB children performed worse than healthy children in terms of the 4 cognitive domains investigated; after 6–12 months of observation, significant improvement in attention-executive function and verbal ability were found in SDB children treated with adenotonsillectomy compared to their baseline level; restoration of attention-executive function and memory were observed in SDB children after adenotonsillectomy in comparison to healthy controls.			
Lee et al ³⁸	3413	younger than 18 years old	sleep architecture and oxygen saturation; respiratory event after surgery; success rate after surgery	polysomnographic findings (sleep architecture) after adenotonsillectomy for obstructive sleep apnoea	obese and non-obese children
	Conclusion	overall success rate was 51% for postoperative AHI <1 (obese versus non-obese versus combined, 34% versus 49% versus 56%), and 81% for AHI <5 (obese versus non-obese versus combined, 61% versus 87% versus 84%)			
Ehsan et al ³⁷	1418			SDB	long-term cardiovascular morbidity; markers for pulmonary hypertension (mPAP), LV diastolic function (mitral E/A), RV dysfunction (RVDd), baroreflex function (RR interval and awake HR), and endothelial dysfunction (C-reactive protein)
	Conclusion	after treatment (most commonly with adenotonsillectomy), these children had significant decreases in mPAP, RVDd, awake HR, RVDd, and C-reactive protein and significant increases in RR interval and mitral Em/Am ratio			
Carter et al ⁴⁰	125,198	between 6 to 19 years		sleep; inadequate sleep quantity; poor sleep quality; and excessive daytime sleepiness	media devices as predictor
	Conclusion	bedtime access and use of media devices was significantly associated with inadequate sleep quantity; poor sleep quality; and excessive daytime sleepiness			
de Azevedo Abreu et al ⁴²	699 to 14,267	11.4 – 21 (2 studies 18+)		sleep duration	dyslipidemia

	Conclusion	lack of consistent evidence regarding the association between sleep duration and lipid profile in adolescents			
Chaput et al ⁴³	592 215	5–17 years	adiposity (n=71), emotional regulation (n=62), cognition/academic achievement (n=6), quality of life/well-being (n=3), harms/injuries (n=4), cardiometabolic biomarkers (n=19)	subjective Sleep duration	health
	Conclusion	longer sleep duration was associated with lower adiposity indicators, better emotional regulation, better academic achievement, and better quality of life/well-being			
Chaput et al ⁴⁴	148524 unique participants	children aged 0 to 4 years	intervention/exposure/comparator; objective (e.g., polysomnography, actigraphy) and subjective (e.g., self-report, proxy-report) measurement	sleep duration	adiposity, emotional regulation, cognitive development, motor development, growth, cardiometabolic health, sedentary behavior, physical activity, quality of life/well-being, and risks/injuries
	Conclusion	shorter sleep duration was associated with higher adiposity (20/31 studies), poorer emotional regulation (13/25 studies), impaired growth (2/2 studies), more screen time (5/5 studies), and higher risk of injuries (2/3 studies). The evidence related to cognitive development, motor development, physical activity, and quality of life/well-being was less clear, with no indicator showing consistent associations; no studies examined the association between sleep duration and cardiometabolic biomarkers in children aged 0 to 4 years			
Felso et al ⁴⁵	21-5777	0-19 years.	obesity (n=23), diet (n=-), physical activity (n=-), screen time(n=2), insulin level/insulin sensitivity (n=4), leptin level (n=2), ghrelin level(n=2)	sleep duration	obesity
	Conclusion	only the link between short sleep duration and the development of insulin resistance, sedentarism and unhealthy dietary patterns could be verified, while the role of other mediators, such as physical activity, screen time, change in ghrelin and leptin levels, remained uncertain			
de Castro Corrêa ⁴⁶	40 - 221	5 to 18.41 years		obstructive sleep apnea (PSG) and 1 questionnaire study	oral language

	Conclusion	most of the phonetic sounds are acquired during ages 3 to 7 years, which is also the peak age for hypertrophy of the tonsils and childhood SDB			
da Silva Gusmao Cardoso et al ⁴⁷		4-16years	cognitive performance (n=13), attention (n=12), memory (n=11), language (n=5), executive functions (n=7), academic performance (n=3), behavioral problems (n=20)	obstructive sleep apnea syndrome	cognitive and behavioral effects
	Conclusion	which specific cognitive ability drives this impairment is unclear, as there was insufficient evidence of deficits in language, memory, attention, executive functions, and academic performance, due to low levels of evidence, conflicting findings, and/or heterogeneity of tasks and cognitive abilities tapped by the measures used to assess these domains			
Saunders et al ⁴⁸	36 560	aged 5–17 years	movement behaviors (n=2), adiposity (n=10), cardiometabolic health (n=1), cardiorespiratory fitness (n=2), musculoskeletal fitness(n=1)	sleep	combinations of physical activity, sedentary behavior
	Conclusion	health benefits were also observed for those with a combination of high physical activity /high sleep (cardiometabolic health and adiposity) or high physical activity /low sedentary behavior (cardiometabolic health, adiposity and fitness), compared with low physical activity /low sleep or low physical activity /high sedentary behavior; of the 3 movement behaviors, physical activity (especially moderate- to vigorous-intensity physical activity) was most consistently associated with desirable health indicators; given the lack of randomized trials, the overall quality of the available evidence was low			
Dolezal et al ⁴⁹	11-12728	lifespan		sleep	exercise
	Conclusion	twenty-nine studies concluded that exercise improved sleep quality or duration; however, four found no difference and one reported a negative impact of exercise on sleep			
Blackwell et al ⁵²	6-117	5-18 years	cognitive outcomes (n=5), psychological outcomes (n=6),	narcolepsy	performance
	Conclusion	narcolepsy significant risk of cognitive impairment in at least one domain and emotional problems including depression, anxiety and low self-esteem			
Angriman et al ⁵³	1-4346	<18 years	kidney diseases, gastrointestinal and liver diseases, diabetes, attention deficit hyperactivity disorder, depression, conduct disorder, migraine, growing pains	restless legs syndrome	somatic and neuropsychiatric comorbidities
	Conclusion	awareness on comorbid diseases/disorders is pivotal to improve the diagnosis and management of restless legs			

syndrome and might suggest fruitful avenues to elucidate the pathophysiology of restless legs syndrome in children

Thorpe et al ¹³	7-2223	0-5 years	night sleep, behavior, cognition, health, cortisol	napping	development and health outcomes included salivary cortisol, night sleep, cognition, behavior, obesity and accidents
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Conclusion

the most consistent finding was an association between napping and later onset, shorter duration and poorer quality of night sleep, with evidence strongest beyond the age of 2 years; the evidence regarding behavior, health and cognition is less certain.

ADHD: attention-deficient hyperactivity disorder; **AHI:** apnea-hypopnea index; **BMI:** body mass index; **CI:** Confidence Interval; **GPA:** grade point average; **IQ:** intelligence quotient; **OR:** odds ratio; **PSG:** polysomnography; **PVT:** psychomotor vigilance test; **RR:** risk ratio; **SDB:** sleep disordered breathing; **x:** number of times

Supplementary Table S3: Measures applied in the papers included

Author	Domain	Measure
Lowe et al	attention	0-back N back, Williams Listening Attention, Visual spatial processing test, Gordon Vigilance, Simple RT, Barrage, Test for Attentional Performance, psychomotor vigilance test, Sustained Attention to Response Task, Divided attention
	executive functioning	1-back, 2-back and 3-back N back, Williams Addition Test, GNG, Staged Information Processing Test, Stroop, Gordon Delay, Simple working memory, Complex verbal working memory, Arithmetic working memory, Tower of London, Trail Making, Mental Arithmetic, Symbol Digit Modalities Arithmetic, Wisconsin Card Sorting Task, Digit Symbol Substitution Task, Digit Span, Go-No-Go
	impulsive decision making memory	Tolerance Test for Creative Thinking Auditory Verbal Learning Task, Williams Word Memory, Verbal and Non-Verbal Memory Test, Verbal Learning and Memory Test, Accuracy Memory Task, California Verbal Learning Test, Wide Range Assessment of Memory and Learning
Short et al ⁶³	full IQ	Stanford Binet Intelligence Scale, Woodcock Johnson III Tests of Cognitive Abilities, Wechsler Intelligence Scale for Children, Wechsler Individual Achievement Test, Wechsler Preschool and Primary Scale of Intelligence, Children's Color Trails Test
	verbal IQ	Stanford Binet Intelligence Scale, A Developmental Neuropsychological Assessment, Woodcock Johnson III Tests of Cognitive Abilities, Stanford Achievement Tests, Wechsler Individual Achievement Test, Wechsler Intelligence Scale for Children, Wechsler Preschool and Primary Scale of Intelligence, Torrance Tests of Creative Thinking, California Verbal Learning Test
	fluid IQ	Stanford Binet Intelligence Scale, Wechsler Intelligence Scale for Children, Wechsler Preschool and Primary Scale of Intelligence, Torrance Tests of Creative Thinking, Continuous Performance Test
	memory	Stanford Binet Intelligence Scale, A Developmental Neuropsychological Assessment, Woodcock Johnson III Tests of Cognitive Abilities, Stanford Achievement Tests, Wechsler Individual Achievement Test, Wechsler Intelligence Scale for Children, Mathematics proficiency, N-Back tasks, Wide Range Assessment of Memory and Learning, Neurobehavioral Evaluation System, Williams Word Memory Test, Teacher-rated academic problems, Symbol Digit Response
	executive function	A Developmental Neuropsychological Assessment, Woodcock Johnson III Tests of Cognitive Abilities, Continuous Performance Test, Wisconsin Card Sorting Test
	processing speed	Stanford Binet Intelligence Scale, Woodcock Johnson III Tests of Cognitive Abilities, Test of Attentional Performance for Children, Sentence reading test, Continuous Performance Test

	attention	Donders Reaction Time, A Developmental Neuropsychological Assessment, d2-test, Conners' Parent Rating Scale, Attention Network Test-Interaction, Listening Attention Task, School Situations Questionnaire, Attention Network, Personal Digital Assistant-Psychomotor Vigilance Task, reaction time
de Bruin et al ⁵⁵	attention restriction studies	psychomotor vigilance test, continuous performance test, digit symbol substitution, Serial alternation, Steer clear, GDS standard delay, Gordon diagnostic system vigilance, Finger tapping test, Simple reaction-time test, test for attentional performance (divided attention/ flexibility), sustained attention, Trail-making test
	attention extension studies	Finger tapping test, Simple reaction-time test, Continuous performance test, Symbol-digit substitution (visual), Baseline speed, Memory search letters (phonol. working memory), Psychomotor vigilance task
	working memory restriction studies	Wilkinson addition test, Wisconsin card sorting test, Visual digit span test, Serial digit learning test, Tower of London, N-back task, Digit span task, Simple verbal working memory, Complex verbal working memory, Arithmetic working memory task, Simple verbal working memory
	working memory extension studies	Visual digit span test, Serial digit learning test, Memory search letters (phonol. working memory), Feature identification (vis.spat. proc.), Spatial temporal span (visual working memory), Category fluency, Letter fluency
	learning and memory restriction studies	Williams word memory test, wide range assessment of memory and learning verbal/visual, Children's category test, Wisconsin card sorting test, California verbal learning test, Serial digit learning test
	learning and memory extension studies	Serial digit learning test, Auditory verbal learning task
	memory consolidation during sleep	English-German vocabulary list, Auditory verbal learning task, Visual verbal memory test, Paired-associate word list task, Mirror tracing task (procedural)
	executive functions restriction studies	Wisconsin card sorting test, Continuous performance test, Gordon diagnostic system vigilance, Gordon diagnostic system standard delay, Tower of London, Trail-making test
	executive functions extension studies	Continuous performance test, Response organization arrows, Category fluency, Letter fluency
	creative/abstract thinking	Children's category test, Wisconsin card sorting test, Torrance test of creative thinking verbal/figural
Tham et al ⁵⁴	cognitive development	Wechsler Preschool and Primary Scale of Intelligence, battery of executive functioning tasks, Mental Development Index of Bayley Scales of Infant Development, working memory task (18 months), working memory, inhibitory control, and set Shifting, Ages and Stages Questionnaire, Language learning task of familiar and novel object-pseudoword pairs, elicited imitation task
Reynaud et al ⁶²	executive function	auditory continuous performance test for preschoolers
	language	Receptive vocabulary, Literacy and numeracy,
	non-specific cognition	General conceptual ability, Non-verbal abilities
	behavior/emotion	Aggressiveness, anger, conduct problems, attention problems, hyperactivity, hyperactivity and impulsivity, impulsivity, opposition, non-specific externalizing behavior, anxious, depressed, emotional symptoms,

withdrawn, shyness, somatization, non-specific internalizing behavior, prosocial behavior, peer relation problems, non-specific behavior problems

Beris et al ⁵¹	performance	(adapted) Epworth Sleepiness Scale, Autism Spectrum Screening Questionnaire, Achenbach Child Behavior Checklist, Children's Depression Inventory, Conners Parent Rating Scale-revised, development and well-being assessment, full scale intelligence quotient, Insomnia Severity Index, Kaufman Assessment Battery for Children, Multiple Sleep Latency Test, Maintenance of Wakefulness Test, Developmental NEuroPSYchological Assessment, nonverbal intelligence quotient, Positive and Negative Syndrome Scale, Pediatric Daytime Sleepiness Scale, Pediatric Quality of Life Inventory, performance intelligence quotient, Perceptual Reasoning Index, Strengths and Difficulties Questionnaire, Stanford Center for Narcolepsy Sleep Inventory, Verbal Comprehension Index, verbal IQ, Vécu et Santé Perçue de l'Adolescent [perceived health-related quality of life in adolescents], Wechsler Adult Intelligence Scale, Wechsler Intelligence Scale for Children, Working Memory Index, Wechsler Preschool and Primary Scale of Intelligence, Wide Range Assessment of Memory and Learning, Wolfson and Carskadon's School Sleep Habits Survey (academic grades extracted)
Schlarb et al ⁶⁵	aggression and antisocial behavior	Achenbach System of Empirically Based Assessment, The Strengths and Difficulties Questionnaire, Symptom Checklist-90-Revised, Brief Symptom Rating Scale, German adapted translation of the M-E-Questionnaire, Adapted version of the M/E Questionnaire, Composite Scale of Morningness, Strength and Difficulties Questionnaire, M/E Scale for Children, Self-rating scale for pubertal development, circadian preference, questionnaire on sleep habits and mental health, Children's Morningness-Eveningness Preferences Scale, WISC-III Subtests, Assessment of salivary cortisol, Diagnostic Interview for Children, Relational Aggression Scale
de Luca Canto et al ⁶⁶	psychosocial factors	Missouri Children's Picture Series, Urinary test of Catecholamines, Kaufman Brief Intelligence Test, Achenbach Child Behavior Checklist, Youth Self Report Questionnaire, Children's Personality Questionnaire, Conners's Parents Rating Scales, Rutter's Child Behavior Scale-A2, Child Stress Scale, Childhood Anxiety Sensitivity Index, State-Trait Anxiety Inventory for Children, Children Depression Inventory
Fatima et al ²⁷	sleep	Children's Sleep Habits Questionnaire, parental report, Self-reported Quality of sleeping time, Sleep Behaviour Questionnaire, Pittsburgh Sleep Quality Index, School Sleep Habits Survey, actigraphy, insomnia Self-assessment Inventory, Self-reported, Sleep problems assessed by three different definitions, Cleveland Adolescent Sleepiness Questionnaire, Sleep efficiency, Chronotype, Sleep pattern inconsistency, sleep diary, Insomnia , obstructive sleep apnoea
623 Quist et al ²⁹	sleep behavior/emotion abdominal adiposity	Questionnaire, Parent-report, 7 nights accelerometry (waist), children's sleep habits questionnaire, sleep log, self-report, 3 nights accelerometry (waist) children's sleep habits questionnaire; pediatric sleep questionnaire, Pittsburgh sleep quality index waist circumference, trunk fat mass index measured by dual x-ray absorptiometry
Sedky et al ³⁵	ADHD	Behavior Rating Inventory of Executive Function; Child Behavior Check List; Conner's parent rating scale; Auditory continuous performance test; Conners' Parent Rating Scales-Revised; child symptom inventory;

		Conner's teacher rating scale; caregiver teacher report; neuropsychological assessment; Clinician disorders
Galland et al ³⁴	SDB	Parent reported frequency of (loud) snoring, Parent reported witnessed apnea, Sleep-Related Breathing Disorder Scale; 4 questions on SDB questionnaire, subscale of Sleep Disturbance Scale for Children, RDI ≥ 1 / with OAI <1 (AT/OSA+) or OAI, 1 (AT/OSA-), SDB severity based on AHI >1 and ≤ 5 , or >5 and ≤ 15 , and AHI >15, Primary snorers (OAI ≤ 1 with snoring history or OAI >1), mild OSAS (1 < OAI ≤ 5) and moderate/severe OSAS (OAI >5), OSA (AHI ≥ 1), UARS (AHI <1 and RDI = 1), primary snoring (AHI and RDI <1 and oxygen desaturation index <4)
	performance	Teacher-reported grades, School report form, School report grade, sum of the latest midterm and final examination scores, Wide Range Achievement Test-3, Parent reported, Wechsler Individualized Achievement Test,
Miller et al ³²	sleep	Parental report, Mixed- child and parent reported, Self-reported, Polysomnography, Accelerometry, interview, time use diary, Computer assisted interview administered by assessors
	obesity	Height and weight measured by researchers, Parental report of height and weight, self-report, Height and weight measured by trained staff
Song et al ³³	cognitive outcomes	Children's Memory Scale; Integrated Visual and Auditory Continuous Performance Test; Chinese Wechsler Abbreviated Scale of Intelligence; Differential Abilities Scales; Kaufman Assessment Battery for Children; Matching Familiar Figures Test; Neuropsychological Developmental Assessment; Stanford Binet Intelligence Scales; Tests of Variables of Attention; Wechsler Abbreviated Scale of Intelligence; Wechsler Individualized Achievement Test; Wechsler Intelligence Scale for Children; Wide Range Achievement Test
Yu et al ³⁹	cognitive	Vocabulary, gestalt closure, number recall, triangles, word order, matrix analogies, spatial memory, sequential processing scale, simultaneous processing scale, mental processing composite, Intelligence, verbal memory, processing speed, attention and executive functioning, Processing speed, visual attention, global executive composite, Intelligence, verbal and nonverbal reasoning ability, attention, executive functioning, memory, processing speed, and visual-motor skill, Full scale IQ, non-verbal IQ, verbal IQ, attention/executive, language, sensorimotor, memory, Peabody Picture Vocabulary Test-III, Delayed visual recall, short-term attention/working memory, and executive functioning, Global intellectual ability, attention, language, visuospatial ability, and sensorimotor skills, memory, executive function, Trail making test, grooved pegboard test, Attention, working memory
de Azevedo	sleep	Questionnaire, actigraphy
Abreu et al ⁴²	lipid profile evaluation	Questionnaire, Blood collection, Capillary blood, collection without fasting
de Castro	oral language	NEPSY, Token Test, Two standardized tests of verbal fluency in Greek, Kaufman Assessment Battery for

Corrêa ⁴⁶		Children Peabody Picture Vocabulary Test
da Silva Gusmao Cardoso et al ⁴⁷	performance	Adaptive Behavior Assessment System-II, Behavior Assessment Scale for Children, Behavior Rating Inventory of Executive Function, Children Behavior Checklist, Children's Memory Scale CogHealth (working memory test), Conners' Parent Behavior Rating Scale Revised: Long Form, Continuous Performance Test, Childhood Symptom Inventory, CaregiverTeacher Report Form For Ages 1.5-5, Conners' Teacher Rating Scale Revised: Long Form, California Verbal Learning Test for Children, Differential Ability Scales, Delis-Kaplan Executive Function System, Expressive Vocabulary Test, Gordon Diagnostic System, Integrated Visual and Auditory Continuous Performance Test, Kaufman Assessment Battery for Children, Luria Auditory Verbal Learning Test, Developmental Neuropsychological Assessment, Peabody Picture Vocabulary Test, Rey Auditory Verbal Learning Test, Rivermead Behavioral Memory Test, Stroop Color and Word Test Children's Version, Sleep disordered breathing, Test of Variables of Attention, Token test, Wechsler Abbreviated Scale of Intelligence, Wisconsin Card Sorting Test, Wechsler Individualized Achievement Test, Wechsler Intelligence Scale for Children, III ed, Wide Range Assessment of Memory and Learning, Wide Range Achievement Test
Saunders et al ⁴⁸	Physical activity	Pedometer, Accelerometer,
124 de Luca Canto et al ⁶⁶	Sleep sedentary behavior	Questionnaire Computer + video game time, Screen time, Accelerometer, questionnaire
Dolezal et al ⁴⁹	exercise	aerobic exercise; resistance training; peak oxygen uptake; = kilocalories per kilogram of body weight per week, triaxial accelerometer
	sleep	daytime sleepiness, times woken from sleep; sleep quality, sleep-onset latency, total sleep time, wake time after sleep onset, sleep efficiency, Epworth Sleepiness Scale, Apnea-Hypopnea Index, Pittsburgh Sleep Quality Index, wrist actigraphy, sleep electroencephalography, Fatigue Severity Scale, polysomnography, Insomnia Severity Index, Johns Hopkins Sleep Survey, antemeridiem (morning), clinician-rated Inventory of Depressive Symptomatology, Patient Reported Outcomes Measurement Information System, Sleep Disturbance Short Form; Helseundersøkelsen i Nord-Trøndelag, Karolinska Sleepiness Scale, Pediatric Daytime Sleepiness Scale
Blackwell et al ⁵²	performance	attention deficit hyperactivity disorder-rating scale, adapted Epworth sleepiness scale, Achenbach child behaviour checklist, child depression inventory, Chalders fatigue scale, Conners parent rating scale-revised, excessive daytime sleepiness, Epworth sleepiness scale, health related quality of life, insomnia severity index, paediatric daytime sleepiness scale, quality assessment score, strength and difficulties questionnaire, Wechsler intelligence scale for children-3 rd edition
Felso et al ⁴⁵	sleep duration obesity	19x min/night, 19x h/day, 7x h/night, 6x min/day, habitual sleep duration, later bedtime, sleep restriction, 6x zBMI (CDC), 2x zBMI (IOTF), 3x zBMI(WHO), 1x BMI (WHO), 5x body fat %, 1x body weight, 3x waist circumference, 1x waist-to-height ratio, 1x abdominal adiposity, 1x weight,2x fat mass, 1x android fat mass, 1x fat mass index, 1x BMI percentile (CDC), 1x sum of skin-folds, 2x BMI, 1x risk of overweight/obese (IOTF), 1x risk of overweight/obese (WHO), 1x weight above weight expected for length, 1x weight to length ratio, 1x

zBMI (reference ?)

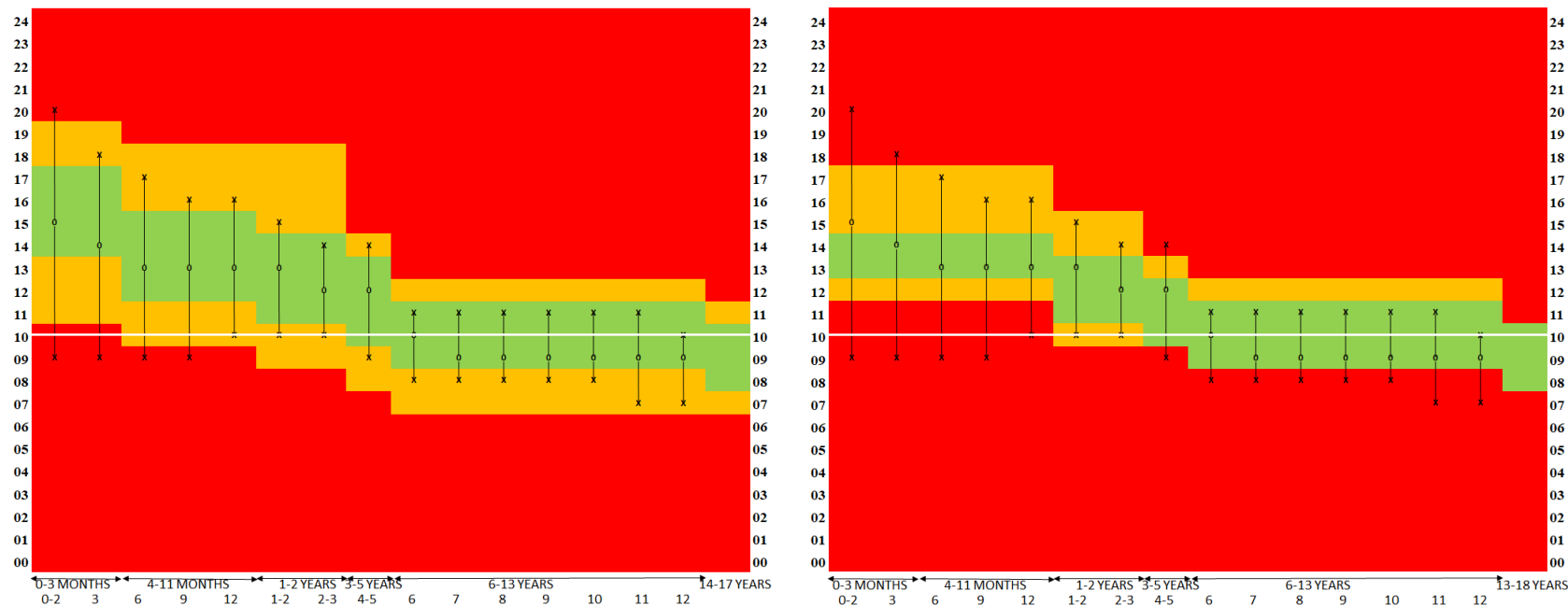
Mietchen et al ³⁶	Gordon Diagnostic System, Integrated Visual and Auditory Continuous Performance Test, Conners' Continuous Performance Test, Behavior Rating Inventory of Executive Function, Wide Range Assessment of Memory and Learning- Second Edition; Controlled Oral Word Association Test, Wisconsin Card Sorting Test, Modified Card Sorting Test
Thorpe et al ¹³	Behavior Assessment System for Children, Bayley Scales of Infant Development, child behavior check list, early childhood education and care
Ruan et al ³⁰	Cleveland Children's Sleep and Health Study, Child Development Supplement, Children's Body composition and Stress, Children's Sleep Habits Questionnaire, sleep disordered breathing, sleep habits questionnaire,
Shochat et al ⁴¹	sleep duration, insomnia, sleep disturbance, sleep problems, bed and wake times, quantity and quality of sleep, sleep habits

CDC: center for disease control; **AHI,** apnea hypopnea index; **AT,** adenotonsillectomy; **HS:** habitual snoring; **IOTF:** international obesity task force; **OAHl:** obstructive apnea hypopnea index; **OAI:** obstructive apnea index; **RDI:** respiratory disturbance index; **SBD:** Sleep-breathing disorder; **x:** number of times; **zBMI:** z-score Body mass index; **UARS:** upper airway resistance syndrome; **WHO:** world health organization;

Supplementary Table S4: Several weaknesses in experimental designs assessing sleep manipulations

- duration of the sleep deprivation
- time on task
- number of sleep deprivation episodes
- time of day
- sleepiness
- lack of macrostructure data
- age-adjusted sleep deficit
- type of task
- lack of micro-structure data
- prospective
- sleep latency
- time awake
- immediate performance
- which part of the night
- assessment tool
- type of sleep restriction
- length of sleep restriction
- developmental salience
- not longitudinal/ cross-sectional design
- duration of task
- complexity of task
- task order
- timing of day
- baseline sleep

Supplementary Figure S1: Guidelines of sleep durations by National Sleep Foundation¹ and American Academy of Sleep Medicine² with superimposed sleep durations across age-bands³

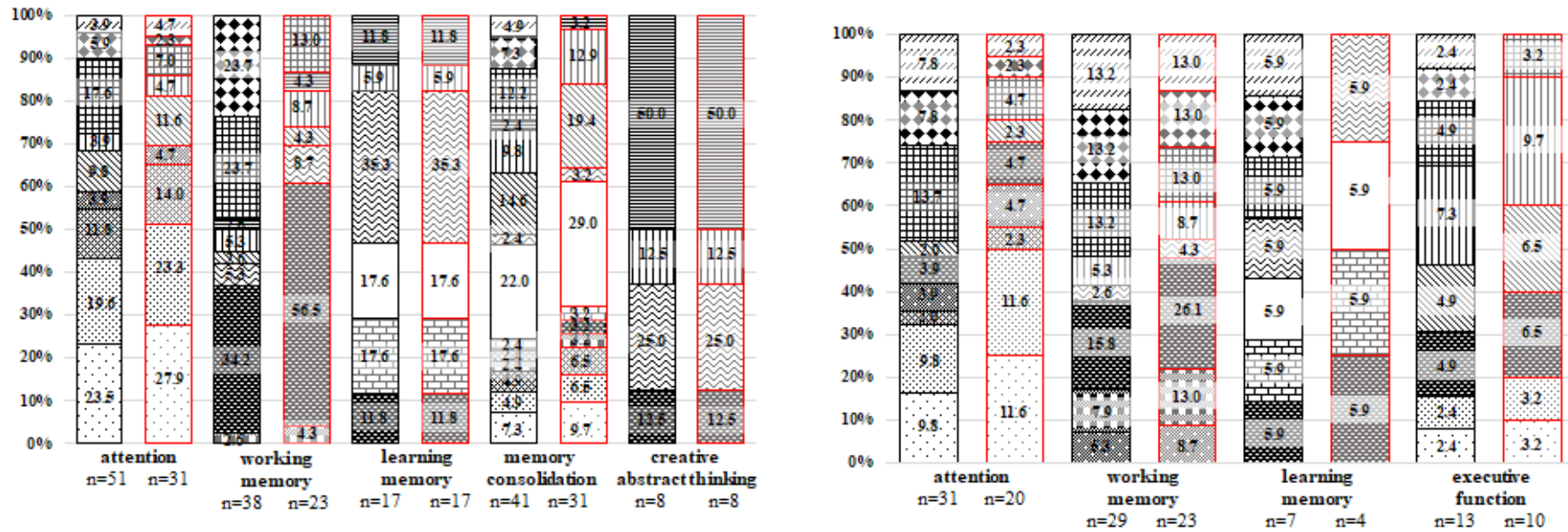


left panel: National Sleep Foundation guideline; **right panel:** American Academy of Sleep Medicine guideline; green: appropriate/recommended; orange: uncertain or disagreement/may be appropriate; red: inappropriate/not recommended; Galland et al³ averaged sleep durations are superimposed with 0: mean and x: lower/upper boundaries; white line: arbitrary cut-off at 10 hours

Supplementary Figure S2: The concept of poor sleep



Supplementary Figure S3: Quantification of a systematic review on neuropsychological outcomes by sleep manipulations in 10-18 year olds



Proportion (%) of neuropsychological domains assessed and affected (in red) across the systematically reviewed studies by de Bruin et al⁵⁵; *left panel*: sleep restriction manipulations; *right panel*: sleep extension manipulations

···· psychomotor vigilance ···· vigilance, sustained attention ···· selective attention ···· divided attention ···· cognitive control, inhibition
 ||||| cognitive flexibility ||||| speed ···· accuracy ···· efficiency ···· visuospatial working memory ···· learning ···· higher, abstract thinking
 ···· memory, immediate recall ···· phonological working memory □ memory delayed recall