The Feasibility of At-home Sleep Extension in Adolescents and Young adults: A Meta-Analysis and Systematic Review

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Summary

Insufficient sleep duration is detrimental to health and performance and is alarmingly common in adolescents and young adults. The aim of this pre-registered meta-analysis was to determine the feasibility of at-home sleep extension as a means to improve sleep duration and daytime sleepiness, and maintain or improve sleep quality and efficiency, in adolescents and young adults. Peer-reviewed journal articles and dissertations were screened to identify studies with at least five consecutive days of at-home sleep extension, pre- and post-extension measurement of sleep duration, and participants 13-30 years of age. Out of 2254 studies assessed for eligibility, 17 met review inclusion criteria – seven in adolescents and ten in young adults. At-home extension of sleep opportunity reliably increased sleep duration and sleep quality, and decreased daytime sleepiness when compared to unmanipulated sleep opportunity. These results indicate that at-home sleep extension is feasible in adolescents and young adults. However, the degree of improvement in sleep duration, sleep quality, and daytime sleepiness varied by study population and sleep extension method, which will have downstream consequences for the effectiveness of sleep extension as an experimental manipulation and intervention to improve health and performance during adolescence and young adulthood.

Keywords: young adult, adolescent, sleep extension, sleep opportunity

Effective public health practice project (EPHPP)

Effect size (ES)

Habitual sleep (HAB)

Preferred reporting items for systematic reviews and meta-analyses (PRISMA)

ProQuest dissertations & theses global (ProQuest)

Sleep extension (EXT)

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Insufficient sleep has negative consequences for health and performance in adolescents and young adults. For example, short sleep duration is associated with infectious illness[1], cardiovascular diseases[2], obesity[3], fatigue[4,5], depressive symptoms[6], mood disturbances[7], and elevated stress response[8]. Insufficient sleep also has detrimental effects on cognitive and psychomotor performance[5], which negatively impacts learning capacity and is associated with poor academic performance[9].

Insufficient sleep is especially common during adolescence and young adulthood. The majority of U.S. adolescents and young adults regularly obtain less than the recommended hours of sleep[10,11]. This is partially due to endogenous delays in the timing of the circadian clock[12,13] without corresponding delays in the start times of daytime social obligations such as school or work. The mismatch between the timing of the circadian clock and the social clock – called “social jetlag” – is prominent during adolescence through the mid-twenties[14]. Social jetlag is also associated with a range of negative health outcomes that increase in prevalence during adolescence and early adulthood, including depression[15], substance use[16], and obesity[17]. These negative health outcomes are leading causes of global disease-related disability and mortality[18].

Widespread associations between insufficient sleep and negative health outcomes suggest that extension of sleep duration could be used as an intervention to reduce sleep debt and improve performance and health outcomes in adolescents and young adults. However, there is conflicting evidence of benefit from sleep extension in laboratory studies. For example, extending sleep opportunity to 12 hr per night for seven consecutive days increased sleep

duration, and improved daytime sleepiness and cognitive performance in young adults in one study[19], while another study in young adults found that extending sleep opportunity to 10 hr per night for seven consecutive days improved daytime fatigue but not daytime sleepiness or mood[20]. In addition, although laboratory sleep extension allows a high degree of control over sleep opportunity and timing, there are numerous characteristics of typical daily living that are difficult to replicate in laboratory settings (e.g., work-leisure routines, social interaction, value-driven behavior and experience), the absence of which may dampen the benefit of extended sleep opportunity. In contrast, at-home sleep extension studies have greater ecological validity, but the feasibility of extending sleep duration may decrease as participants' autonomy increases, and at-home extension of sleep duration may be particularly challenging during adolescence and young adulthood due to social jetlag. Although sleep extension protocols are typically used as time-limited experimental manipulations to evaluate sleep as a causal predictor of specific outcomes, in contrast to clinical interventions which seek to change sleep more permanently, the feasibility of at-home sleep extension is important to establish for research applications as well as clinical interventions for insufficient sleep or other health and performance outcomes.

Recent studies have begun to evaluate the effects of at-home sleep extension on sleep and health outcomes, often within populations that are at high risk for insufficient sleep, such as adolescents and young adults. In light of this growing research base and the potential benefits of sleep extension for public health, the primary aim of this meta-analysis was to determine whether and when at home extension of sleep opportunity is a feasible means of extending sleep duration in adolescents and young adults. A second aim was to summarize the effects of extended sleep opportunity on secondary sleep outcomes (e.g., sleep opportunity time, sleep efficiency, sleep quality, daytime sleepiness). A third and final aim was to provide a qualitative summary of the

health and performance outcomes that have been examined in studies of sleep extension in adolescents and young adults.

Method

Study Identification and Screening

A pre-registration following Preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines[21] was submitted in August 2019 (PROSPERO registration number: CRD42020145625). Electronic bibliographic databases of PsycINFO and PubMed were employed to review potential eligible peer-reviewed journals published after 1900. Unpublished doctoral dissertations after 1900 were searched on ProQuest dissertations & theses global (ProQuest). PsycINFO and PubMed were used to search titles, abstracts, and keywords using the terms (“sleep exten*” OR “extension of sleep” OR “extended sleep”), where the asterisk is a wild-card character. One of the search terms, “sleep exten*” was replaced with “sleep extension” in ProQuest to accommodate the search algorithm in this database. Initial study identification was conducted in August 2019, then repeated in March and August 2020 to identify studies published since the initial search. Forward and backward referencing of eligible studies was used to supplement database searches. In addition, corresponding authors of eligible studies were contacted by email to inquire about manuscripts that may not have been identified in the database search. For any corresponding authors that did not reply to the request email, sleep-related publications of the author were searched and screened. Abstracts, full texts and supplemental material were screened for full eligibility.

Eligibility

Studies were included in this meta-analysis if they had: 1) experimental research designs with quantitative sleep duration data from at least 5 consecutive days of habitual/baseline sleep

and 5 consecutive days of sleep extension; 2) random assignment to habitual sleep opportunity versus extended sleep opportunity for between-group comparisons, and either random or sequential assignment to conditions for within-subject comparisons; 3) samples with a mean age between 13-30y; and 4) were available in full-text in English. Studies were excluded if: 1) sleep extension was not conducted at home for at least 50% of the sleep extension period; or 2) sleep extension was implemented incrementally (e.g., 15 min extra sleep opportunity on day 1, 30 min extra sleep opportunity on day 2, etcetera) rather than acutely and consistently (e.g., 90 min extra sleep opportunity each day for five days) because effect sizes for average sleep duration in incremental protocols are not comparable to effect sizes in acute protocols.

Data Extraction

Data extraction included independent double-coding of each study by the two first-authors (X. N. & S. Z.) and included: 1) sample information (e.g., recruited sample size, sample size included in analysis, population of interest, demographic characteristics, inclusion and exclusion criteria); 2) sleep manipulation method (e.g., type of extension, extension design, restriction design if applicable, average number of days designed for each study condition, intended sleep opportunity per night during each experimental condition); 3) list of sleep measures included in each study; 4) pre- and post-intervention sleep duration outcomes; and 5) secondary sleep outcomes if available (i.e., pre- and post-intervention sleep opportunity, sleep efficiency, sleep quality, daytime sleepiness). For studies that had both baseline (i.e. non-experimental condition for sleep monitoring or stabilization before experimental conditions) and habitual sleep (i.e. experimental condition with unmanipulated sleep opportunity), data from habitual sleep were coded to compare with extended sleep. Studies of between-subject designs were coded for additional information including: 1) sample size and age in each manipulation

group; 2) the average number of days in each manipulation group; and 3) prescribed sleep opportunity per night in each sleep condition. If multiple publications were based on the same dataset, the following criteria were considered to decide which publication to use for data extraction of primary and secondary sleep outcomes, in order of priority: 1) ability to assess the effect of sleep extension on sleep duration; 2) sample size, where larger samples were prioritized; and 3) ability to evaluate the effect of sleep extension on secondary outcomes, such as sleep quality. Additional publications from the same dataset were examined for the third aim of the review (i.e. qualitative summary of additional health and performance benefit from sleep extension) if any of them included data on health and performance outcomes from both habitual sleep opportunity and extended sleep opportunity.

Study Quality Ratings

Consistent with PRISMA guidelines[21], quality ratings were conducted for each study, independently by the two first authors (X. N., S. Z.). Discrepancies were resolved using quality ratings from the senior author (M. C.) with consensus discussion when needed. The Effective public health practice project (EPHPP) quality assessment tool[22] was used to evaluate the quality of the study designs using component scores for the following: 1) participants (selection bias, withdraw and dropouts); 2) methodology (study design and data collection); and 3) analyses. Each sub-component was examined on a 3-point scale as strong (three points), moderate (two points), and weak (one point). The rating of global study quality was the average of the sub-components. Consistent with EPHPP guidelines, if a study failed to provide information to rate a component, that component was rated as weak.

Specific criteria for rating the methodology component were developed to capture the best practice of experimental designs and sleep data collection. In the study design rating, within-

subject studies that employed counterbalanced designs to randomize the order of experimental conditions (i.e., habitual sleep and extended sleep) received higher ratings than those studies without counterbalanced designs, because counterbalancing is recommended to minimize sequential effects across experimental conditions in within-subject designs[23]. Within-subject studies that only had a baseline assessment to compare with sleep extension (i.e. non-experimental unmanipulated sleep that preceded experimental sleep manipulation) received the same study design rating as within-subject studies without counterbalanced designs.

Additionally, studies that used both objective (i.e., actigraphy) and subjective (i.e., sleep diary) measures of sleep duration were rated as strong in data collection. Studies with only actigraphy were rated as moderate, and studies with only sleep diary were rated as weak for the data collection component. These criteria were adopted because previous reviews indicate that actigraphy provides more accurate estimates of sleep duration than sleep diaries across various situations and populations[24].

Analysis

Interpretation of Effect Size

Between-subject and within-subject effects of habitual sleep versus sleep extension were expressed using Cohen's d effect size (ES) for the for the following six variables: 1) actigraphic sleep duration; 2) self-reported sleep duration; 3) sleep opportunity (hours between bedtime and rise time); 4) sleep efficiency (sleep duration/sleep opportunity); 5) sleep quality; and 6) daytime sleepiness. The sign of the effect size indicates the direction of changes in the corresponding measures and does not represent improvements or worsening of symptoms (e.g., a negative effect on daytime sleepiness indicates both a decline and improvement of the symptoms). The value of the effect size quantifies the magnitude of standard differences between two sleep conditions,

with 0.01 indicating very small effects, 0.20 indicating small effects, 0.50 indicating moderate effects, 0.80 indicating large effects, 1.20 indicating very large effects, and 2.00 indicating huge effects[25,26].

Calculation of Effect Size

Individual effect sizes for each study were calculated following the guidelines recommended by Lipsey and Wilson[27] (specific formulas available in “supplemental material”). Next, a meta-analysis was conducted to combine individual effect sizes and inverse variance weights. The means, z scores, and confidence intervals of the effect sizes were computed by a macro within SPSS developed by Lipsey and Wilson[27]. The threshold for statistical significance was set to $p < .05$, two-tailed.

Effect Size Homogeneity

The Q statistic, which was distributed as a chi-square, was calculated to assess the homogeneity of the effect size distribution[27]. When Q was significant ($p < .05$), the variability of the effect size was greater than what would be expected from sampling error. The Q statistic was not conducted for sleep variables that were assessed by only one study.

Publication Bias of Effect Size

Publication bias of within-subject effect sizes on actigraphic sleep duration was examined by the funnel plot and *fail-safe N* statistic. The funnel plot is a scatterplot that demonstrates study effect size against its precision, and deviance from the funnel-shaped distribution (i.e., asymmetry) can indicate publication bias[28]. The *fail-safe N* statistic determines the number of unpublished studies with null results needed to reduce the combined effect size to the point of non-significance (see formula in “supplemental material”)[27].

Results

Study Identification and Review

Figure S1 includes a CONSORT flow diagram of the search and eligibility results. In total, 17 independent studies were included in this meta-analysis. Database searches identified a total of 723 reports, 17 of which met all inclusion criteria. Forward and backward referencing and citations from corresponding authors identified a total of 1531 reports, eight of which were eligible for review. The majority of reports were excluded because they did not implement a direct manipulation of sleep opportunity (81%, $n=1816$). Eight of the eligible studies that reported overlapping data within the sleep outcome domain from another study sample were excluded from the meta-analysis of sleep duration, although two of were included for review of health and performance outcomes[29,30].

Study Description

Sample Characteristics

A summary of subject demographic information is shown in “table 1”. This review included seven studies in adolescents (10-17y of age, $M_{age}=14.98$) and ten in young adults (18-31y of age, $M_{age}=21.68$). Of the 17 studies, five (29%) intended to recruit short sleepers (e.g., adolescents who regularly obtained five to seven hours of sleep on school nights), five (29%) intended to recruit healthy individuals who typically obtained sufficient sleep, four (24%) specifically examined young adult athletes, and three (18%) included those with physical health conditions. None of the studies included participants with sleep disorders. Sample sizes ranged from 10 to 106 participants ($M=35.59$, $SD=28.33$). Based on objective habitual sleep duration or subjective sleep duration if actigraphy data were not available (“table 3” and “table 4”), 86% of studies of adolescents and 60% of studies of young adults were characterized by participants who

habitually obtained less than adequate sleep duration per standards from the National Sleep Foundation (i.e. 8-10 hours for adolescents, 7-9 hours for young adults)[10].

Study Design

A majority of studies ($n=14$) had within-subject designs; three studies had both between-subject and within-subject designs[31–33]. Of the 17 within-subject studies, six[34–39] used counterbalancing to randomize the order of habitual sleep (HAB) and extended sleep (EXT) conditions; the remaining 11 maintained the same order of sleep conditions (i.e., HAB followed by EXT).

Intervention Design

The 17 studies varied in intervention design (“Table 2”): nine (53%) had a targeted sleep duration (range: 8.5-10 hr per night), seven (41%) extended sleep opportunity by a specific amount (range: 1-1.5 hr per night), and one (6%) encouraged as much sleep as possible. There was variability between studies in specifying whether sleep was conducted with lights out or electronic screens off, naps were avoided, bedtime was advanced with or without delayed waketime, caffeine consumption was regulated, or sleep education and consultation were provided. The number of days of sleep manipulation ranged from 5 to 49 nights ($M=14.29$, $SD=15.16$), with 41% of the studies ($n=7$) including seven nights of sleep extension (modal duration of sleep extension).

Study Quality

Quality ratings for participant selection ranged from 1 to 2.5 ($M=1.79$). The most frequent rating was 2 (i.e., moderate), accounting for 53% of the studies ($n=9$). The vast majority of the studies (94%, $n=16$) were rated as weak for selection bias because they only included self-

referred participants. Most studies (59%, $n=10$) had study completion rates over 80%, and were therefore rated as strong for study retention.

Quality ratings for methodology ranged from 1.5 to 3 ($M=2.29$). The most frequent ratings were 2 (i.e., moderate) and 2.5 (i.e., moderate to strong), each of which was received by 41% of the studies ($n=7$). Most studies (76%, $n=13$) were rated as moderate for study design because they were within-subject studies that only included non-experimental baseline conditions or did not counterbalance the order of the two experimental conditions (i.e., habitual sleep and extended sleep). Only 24% of the studies ($n=4$) were rated as strong for study design because they were either between-subject studies with random group assignment or within-subject studies with counterbalanced order of habitual sleep and sleep extension conditions. Seven studies (41%) were rated as strong for data collection because both actigraphic and self-reported sleep duration were collected, nine (53%) were rated as moderate for only including actigraphic measures of sleep, and one (6%) was rated as weak for only including self-reported sleep.

All 17 studies were rated as strong for analyses and received quality ratings of 3 because they conducted the appropriate quantitative analyses for the research questions being asked[22]. Specifically, between-subject studies conducted independent sample t -tests to compare sleep, health, and performance in the habitual sleep group versus the sleep extension group; within-subject studies conducted paired sample t -tests to determine whether there were significant changes in outcomes during extended sleep periods; and studies that were interested in analyzing both within-subject and between-subject effects incorporated the pretest-posttest control group design and conducted ANCOVA to examine the change from pre-intervention in both the habitual sleep and the sleep extension groups.

Homogeneity Tests

The distribution of effect sizes was found to be heterogeneous for the three studies with between-subject comparisons: $Q(2)=717.47, p<.01$ for actigraphic sleep duration; $Q(1)=694.06, p<.001$ for sleep opportunity; $Q(2)=823.74, p<.001$ for sleep efficiency; $Q(1)=114.20, p<.001$ for sleep quality. There was also significant heterogeneity in the within-subject effect sizes for actigraphic sleep duration, $Q(13)=131.82, p<.01$; sleep opportunity, $Q(5)=102.51, p<.001$; sleep efficiency, $Q(11)=94.26, p<.001$; and daytime sleepiness, $Q(7)=52.65, p<.001$. The distribution of effect sizes was found to be homogenous in the within-subject comparisons for self-report sleep duration, $Q(6)=2.09, p=.911$; and sleep quality, $Q(2)=1.79, p=.408$, indicating that the variance of effect sizes on self-reported duration and sleep quality was no greater than what would be expected from sampling error alone.

Publication Bias

Figure 1 demonstrates an asymmetrical funnel plot for within-subject effects of sleep extension on actigraphic sleep duration. The number of studies with an effect size of zero needed to reduce the combined effect size to a non-significant level was 13.

Effects of Extended Sleep Opportunity on Total Sleep Time

Means and standard deviations are reported in “table 3” for between-subject effects, and “table 4” for within-subject effects. A summary of effect sizes, confidence intervals, and z -scores is shown in “table 5” (between-subject effects) and “table 6” (within-subject effects).

Overall, the magnitude of the mean effect size for actigraphic sleep duration was moderate for between-subject studies and large for within-subject studies. On average across between-subject studies with actigraphy, participants in the sleep extension group were able to sleep 31 min longer than participants in the control group, with effect sizes ranging from

moderate to huge. In the 14 within-subject studies that provided actigraphic sleep duration data, the average sleep duration measured by actigraphy was 55 min longer during sleep extension compared to habitual sleep, and was also represented by moderate to huge effects; See Figure 2.

Sleep duration was assessed by sleep diary in one between-subject study and seven within-subject studies. The between-subject study found huge increases in self-reported sleep duration, and the within-subject studies found either very large or huge increases. Compared to their typical sleep, participants obtained 1.80 hr more sleep on average during sleep extension when measured by sleep diary.

Effects of Extended Sleep Opportunity on Secondary Sleep Outcomes

Sleep Opportunity

In addition to sleep duration, sleep extension was associated with increases in sleep opportunity time. The two between-subject studies found moderate to very large differences in sleep opportunity time, and the six within-subject studies found small to huge differences. On average, there was a moderate improvement of sleep opportunity in between-subject studies: the sleep extension group achieved 40 min more time in bed than the control group. On average across within-subject studies, sleep extension had a moderate effect on sleep opportunity: participants increased time in bed by 57 min.

Sleep Efficiency

Most studies (73%) demonstrated that sleep extension was associated with decreases in sleep efficiency, but the magnitude of the mean effect size was small for both between- and within-subject studies. Sleep efficiency was calculated and reported by three between-subject studies and 12 within-subject studies. Of the between-subject studies, one found a very small increase, while two found statistically large decreases. On average, participants in the sleep

extension group reported sleep efficiency that was 0.61% lower than the control group. Of the within-subject studies, one did not find any difference, nine found decreases that ranged from very small to moderate, one found a very small increase, and one found a statistically large increase. Sleep efficiency was on average 1.37% lower during sleep extension compared to habitual sleep.

Sleep Quality

The two between-subject studies and three within-subject studies that assessed and reported sleep quality all demonstrated improved sleep quality after extension of sleep opportunity. The magnitude of the mean effect size on sleep quality was moderate for between-subject studies and small for within-subject studies. Between-subject studies indicated moderate to large increases in sleep quality, whereas effect sizes of within-subject studies ranged from very small to small.

Daytime Sleepiness

Most studies (89%) found that sleep extension was associated with beneficial changes in daytime sleepiness. Daytime sleepiness was reported by one between-subject study that found a moderate improvement after extension of sleep opportunity. Of the eight within-subject studies that assessed daytime sleepiness, the majority ($n=7$) found decreases in daytime sleepiness that ranged from very small to huge, and only one found very small increases. On average, within-subject studies found a small decrease in daytime sleepiness after sleep extension.

Effects of Extended Sleep Opportunity on Health and Performance

A summary of health and performance outcomes that have been examined in the studies of sleep extension is shown in “Table S1”. The five studies in adolescents examined the effect of at-home sleep extension on externalizing and internalizing symptoms, cognitive function, and

physical activity[29,30,33,37,38]. These studies indicated that sleep extension improved problems regarding inattention, hyperactivity, and oppositionality/irritability[38], as well as symptoms of anxiety, depression, withdrawal, and emotional self-control[33]. Habitually short-sleeping adolescents experienced improved anger, vigor, fatigue, and confusion when they obtained more sleep[37]. After extension of sleep opportunity, adolescents demonstrated improvements in sluggish cognitive tempo and fewer driving problems[29]. Additionally, adolescents spent less time engaging in sedentary behaviors during sleep extension than habitual sleep[30].

The four studies in young-adult athletes indicated that extending sleep opportunity is an effective way to improve athletic performance in collegiate or professional athletes[40–43]. During extended sleep relative to habitual sleep, athletes demonstrated faster reaction time, better peak performance, increased vigor, decreased fatigue, better mood[40,43], and decreased physiological stress[42]. Sleep extension was also associated with increased caloric intake with increased percentage of total fat[43].

The six studies in non-athlete young adults examined a variety of health outcomes. Sleep extension was associated with beneficial impacts on glucose metabolism and insulin sensitivity[44]. Young adults were able to reduce dietary intake of fat, salt, carbohydrates, and free sugars after the extension of sleep opportunity, suggesting that sleep extension was associated with behavioral changes that were conducive to maintenance of weight[31,45]. Sleep extension also improved cardiovascular functioning, including blood pressure and heart rate[46]. Young women with insufficient sleep and depressive symptoms demonstrated improved affect following the sleep extension period, including less severe depression symptoms and anhedonia, as well as higher morning positive affect[32]. In other samples of young adults, sleep extension

improved vigor, fatigue, and mood[45], and improved reaction time on a psychomotor vigilance task[47].

Discussion

This meta-analysis investigated the feasibility and potential benefits of at-home extension of sleep opportunity in adolescents and young adults. Although the reviewed studies varied largely in sample characteristics, intervention designs, and study length, all of them reported an increase in sleep duration given additional sleep opportunity. Extended sleep opportunity also generally improved daytime sleepiness and sleep quality, with varied effects on sleep efficiency.

Effects of Extended Sleep Opportunity on Sleep Duration

Within-subject effect sizes of sleep extension on sleep duration ranged widely across studies, representing 26 to 115 min of additional sleep time. Six out of eight studies that had increases of 60 min or more in sleep duration were conducted on habitual short sleepers. Between-subject effect sizes of sleep extension on sleep duration also ranged widely, representing an increase of 7.2 to 61.2 min of additional sleep time. Two out of three studies were conducted on habitual short sleepers. The large to huge effects in short sleepers within and across groups likely reflect the higher degree of sleep debt in this population compared to those with longer habitual sleep[48].

Many reviewed studies included sleep education or consultation as supplements to direct sleep manipulation[31,33,37,42,44,45]. However, studies indicated successful increases in sleep duration regardless of whether supplemental sleep education or consultation was included in sleep interventions. Although evidence is mixed, sleep education and sleep hygiene can be effective in promoting healthier sleep behaviors and improving sleep outcomes[49,50]. For example, the study by Tasali et al. had the largest effect size and included restriction of bedtime

electronics usage[45], but it is unclear whether integrating other components of sleep education is a helpful supplement to direct prescriptions to extend sleep opportunity.

Effects of Extended Sleep Opportunity on Secondary Sleep Outcomes

Extension of sleep opportunity can lower sleep efficiency due to a reduction in homeostatic sleep drive[51]. Therefore, it is not surprising to see an inverse relationship between sleep extension and sleep efficiency in most of the reviewed studies. However, there was an exception of almost five percent increase in sleep efficiency after sleep extension in Swinbourne et al.[42] with short-sleeping rugby players. The pre- and post-intervention sleep efficiencies of the sample of rugby players were both below 80%, while participants in other studies all had sleep efficiencies that were at least 80% for both pre- and post-intervention. The extension-related increase in sleep efficiency in a sample with relatively poor sleep efficiency suggests that sleep extension may benefit sleep efficiency in populations suffering from poor normative sleep behaviors and sleep debt, such as athletes[42,52].

Most of the reviewed findings indicated that sleep extension was associated with moderate or large improvements in daytime sleepiness. One exception was Casement et al.[32], which only found a small improvement in daytime sleepiness in within-group comparisons and moderate differences in between-group comparisons. A possible explanation for this difference may be the target population of this particular study – rather than targeting healthy young adults, Casement et al.[32] recruited a sample of young women with insufficient sleep, depressive symptoms, and daytime sleepiness at or above population averages. Sleep-deprived individuals with depressive symptoms are more likely to develop daytime sleepiness than healthy populations[53], and may be less likely to show improvement in daytime sleepiness from sleep extension due to other contributing factors (e.g., fatigue in the context of depression).

Swinbourne et al.[42] was another exception that showed no significant improvement in daytime sleepiness after sleep extension in male rugby players, which suggested that the effect on daytime sleepiness may vary significantly across populations (e.g., individual differences in sports training).

Effects of Extended Sleep Opportunity on Health and Performance Outcomes

Sleep extension has additional benefits for health and performance other than its benefits for sleep. Although not all of the health outcomes examined by reviewed studies were improved by sleep extension, the aggregate results suggest that sleep extension has clinical and performance benefits across ages and populations. For example, improvements in psychological distress (e.g., anxiety, depression, stress), vigor, and fatigue were found in studies of adolescents and young adults. In addition, although most studies in this review were completed with general populations of adolescents and young adults, three studies of athletes indicated that sleep extension improved health and athletic performance.

Insufficient Sleep in Adolescent and Young adults

Adolescents and young adults are particularly prone to insufficient sleep compared to other age groups due to both intrinsic factors (e.g. sleep phase delay and sleep pattern disruption related to pubertal hormonal changes)[54] and extrinsic factors (e.g. increased accessibility of electronic devices, caffeine consumption, increased bedtime autonomy). The resulting sleep insufficiency and social jetlag [14,55,56] can increase risk for severe physical and mental health problems such as depression, obesity, and higher rates of drowsy driving accidents[56].

Compared to adolescents, young adults may face extra risk factors that contribute to sleep debt including increased work demands, social commitments and changes of family dynamics during adulthood[55]. At-home sleep extension protocols provided adolescents and young adults the

opportunity to change their sleep behavior in the environment that is the closest to free living. However, the experimental sleep extension protocols reviewed here provide incentives that are not typical of everyday life (e.g., monetary compensation, daily bedtime and wake time reminders and/or questionnaires) and the protocols were time-limited. Immediate incentives for adequate and regular sleep opportunity and daily bedtime and wake time reminders could be incorporated into clinical protocols (e.g., parent- or clinician-provided incentives and reminders, digital applications, system-wide delays in school start-times). Extension of sleep opportunity can also be recommended in sleep health promotion programs that aim to address insufficient sleep in adolescents and young adults[57]. Across both age groups, sleep extension may help to minimize future adverse outcomes that can result from cumulative sleep debt.

Strengths and Limitations of Existing Studies

Despite variations in study designs, the effects of acute sleep extension on sleep duration were quite consistent and show that acute sleep extension is a feasible intervention to increase sleep duration. There was also general convergence across studies in the method of sleep extension (i.e., extend sleep opportunity by a specified amount of time or to a specified number of hours), with only one study instructing participants to extend sleep opportunity as much as possible. Dissimilarities in study designs were relatively minor and included variations in use of sleep education/consultation, instructions about naps, electronic screen exposure, and light exposure, and length of extension. However, the range in approaches to sleep extension and small number of overall studies also make it difficult to identify which extension design features are beneficial. For example, more days of sleep extension may be optimal for robust differences to emerge but may also reduce participants' capability and need to maintain extended sleep schedules; as sleep debt is gradually paid, there may be a gradual decrease in sleep duration and

sleep efficiency with extended time in bed[47]. However, the four studies in this review that included long sleep extension periods (i.e., more than the average 14-day length of extension) demonstrated effects that were similar to other studies[31,40,42,44]. Advancing bedtime may also lead to a shift in circadian timing, which may provide benefits beyond extending sleep duration, including improvements in daytime sleepiness and fatigue[58]. It is difficult to disaggregate the effects of sleep duration from sleep timing in existing research.

Although there are encouraging results of sleep extension on various sleep and health outcomes in existing studies, there are some common limitations to the quality of extant research. First, a vast majority of studies included self-referred participants, which resulted in lower quality rating scores for the participant component in all reviewed studies and raises concerns about selection bias and generalizability[22]. Self-referred participation in sleep extension studies is likely biased towards people who have desire or intent to extend their sleep duration. The results of sleep extension in these samples may not generalize to people who do not have the desire or intent to improve their sleep. In addition, although the range of effect sizes in studies with compensation[31–33,37,38,41,46] was the same as studies that did not mention compensation explicitly, it is unclear whether the benefits of sleep extension persist in the absence of monetary incentives, daily bedtime and wake-time reminders, and accountability to the researchers.

Strengths and Limitations of this Meta-Analysis

The present review provides a much-needed synthesis of the effectiveness of at-home sleep extension and its effects on sleep and health outcomes in adolescents and young adults. The review captured a diversity of studies and samples and is also the first to meticulously evaluate different research methodologies for at-home sleep extension. Although reduced feasibility (e.g.

capability to maintain sleep extension schedules) is one of the concerns associated with at-home sleep extension relative to laboratory extension, the present review indicates that at-home sleep extension is a feasible means of extending sleep duration, even in populations for whom it might be a particular challenge to maintain extended sleep opportunity (e.g., college athletes, individuals with depressive symptoms). A limitation of the present review is the relatively small number of studies, especially in adolescents. Based on the asymmetry of the funnel plot of effect sizes, this review may overrepresent published works with statistically significant findings and have potential upward bias for the mean effect size. This review was also limited to acute and continuous sleep extension, so the conclusions cannot be generalized to other types of direct sleep manipulation (e.g., incremental sleep extension).

Future Directions and Conclusion

Future studies should continue investigating sleep extension as a preventative intervention that helps maintain sufficient sleep and prevent adverse health outcomes in the long term. This work should consider how the developmental stage of the target population is likely to affect the feasibility and reliability of the effects on health and performance outcomes. Individual differences (e.g., circadian timing, sleep need, social responsibilities) should also be considered when identifying the best design for sleep extension (e.g., optimal time in bed and sleep timing) across ages and populations. Additionally, follow-up studies may be considered to examine the adherence to greater sleep opportunity beyond experimental protocols without objective monitoring of sleep and monetary compensation.

Practice points:

1. Sleep extension is a feasible intervention for adolescents and young adults to increase sleep duration without negative impact on sleep quality.
2. Sleep extension may have benefits for mental and physical health.

Research Agenda:

1. Studies of sleep extension in adolescents could help establish both the short- and long-term consequences of sleep extension on sleep behaviors and other aspects of physical and mental health into adulthood.
2. The heterogeneity in study effect sizes suggest that replication studies are needed to fully evaluate the feasibility and benefits of sleep extension while accounting for individual differences in sleep debt, sleep timing, and social circumstances that impact sleep opportunity and sleep duration.

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Figure 1. Funnel plot for within-subject effects of sleep extension on actigraphic sleep duration.

Dots represent individual studies. The y-axis represents study precision with standard error. The x-axis represents the study's effect size.

Figure 2. Error bar chart with effect sizes and 95% confidence intervals for within-subject effects of sleep extension on actigraphic sleep duration.

Table 1
Descriptive Characteristics of the Samples

	Age, <i>M</i> (range)	Sample size (<i>n</i> , female)	Attrition, %	Sample description	Study quality
Adolescence (<i>n</i>=7)					
Becker et al. (2019) ^[35]	15.2 (14.0–17.0)	48 (12)	33.3%	adolescent diagnosed with ADHD	1.5/2.5/3.0
Beebe et al. (2008) ^[38]	15.2 (13.9–16.8)	19 (8)	5.0%	healthy adolescents	2.0/2.5/3.0
Beebe et al. (2017) ^[36]	15.5 (14.0–16.9)	87 (57)	25.0%	healthy adolescents	1.5/2.0/3.0
Frye (2017) ^[33]	13.5 (10.0–16.0)	106 (50)	4.5%	youth with type 1 diabetes	2.5/3.0/3.0
Meltzer et al. (2015) ^[34]	13.7 (12.0–17.0)	10 (6)	37.5%	adolescents with asthma	1.5/2.0/3.0
Meltzer et al. (2020) ^[39]	14.7 (12.0–17.0)	54 (37)	41.3%	adolescents with asthma	1.0/2.0/3.0
Van Dyk et al. (2017) ^[37]	15.9 (-)	54 (33)	28.9%	short-sleeping adolescents	1.5/2.5/3.0
Young Adulthood (<i>n</i>=10)					
Al Khatib et al. (2018) ^[31]	24.5 (21.5–30.1)	42 (35)	8.7%	short-sleeping young adults	2.0/2.5/3.0
Casement et al. (2020) ^[32]	20.0 (18.0–22.0)	22 (22)	31.3%	short-sleeping women with depressive symptoms	1.5/3.0/3.0
Famodu (2014) ^[43]	20.2 (18.0–23.0)	21 (21)	16.0%	female track athletes	2.0/2.0/3.0
Kamdar et al. (2004) ^[47]	20.1 (18.0–23.0)	15 (4)	0.0%	healthy, normal sleeping college students	2.0/2.5/3.0
Leprout et al. (2015) ^[44]	25.0 (23.0–27.8)	16 (13)	5.9%	non-obese, night-shift workers	2.0/2.5/3.0
Mah et al. (2011) ^[40]	19.4 (18.0–22.0)	11 (0)	15.4%	college basketball players	2.0/2.5/3.0
Schwartz & Simon (2015) ^[41]	20.2 (18.0–22.0)	12 (7)	0.0%	college varsity tennis players	2.0/1.5/3.0
Stock et al. (2020) ^[46]	20.5 (18.0–23.0)	53 (37)	7.0%	healthy college students	2.0/2.0/3.0
Swinbourne et al. (2018) ^[42]	25.0 (-)	25 (0)	0.0%	professional rugby players	1.5/2.0/3.0
Tasali et al. (2014) ^[45]	28.6 (-)	10 (5)	9.1%	overweight, short-sleeping young adults	2.0/2.0/3.0

Note. ADHD, Attention deficit hyperactivity disorder. Attrition, the percentage of participants who dropped out of the study before the study completed. Sample size, the number of participants who completed the study (the number of female participants in the sample). Study quality, ratings for participants/methodology/analyses. “-”, information is not provided in the original report.

Table 2
Intervention Design and Length

	Intervention design	Intervention length, days
Adolescence (n=7)		
Becker et al. (2019) ^[35]	Adjust bedtime to obtain 9 hr of nightly sleep	5
Beebe et al. (2008) ^[38]	Extend sleep opportunity to 10 hr with lights out	5
Beebe et al. (2017) ^[36]	Change prescribed bedtimes on school nights to allow 10 hr in bed with lights out and all phones and electronic screens off	5
Frye (2017) ^[33]	Extend sleep opportunity to 10 hr or one hour more than their sleep duration during the baseline measure	7
Meltzer et al. (2015) ^[34]	Extend sleep opportunity with lights out to 10 hr	5
Meltzer et al. (2020) ^[39]	Advance bedtime that allows 9.5 hr of sleep opportunity and not nap	7
Van Dyk et al. (2017) ^[37]	Extend sleep opportunity by 1.5 hr on school nights	10
Young Adulthood (n=10)		
Al Khatib et al. (2018) ^[31]	Extend sleep opportunity by 1-1.5 hr	35
Casement et al. (2020) ^[32]	Extend sleep opportunity by 1.5 hr, including weekends	7
Famodu (2014) ^[43]	Obtain one more hour of sleep by advancing bedtimes, forming healthy sleep habits, or delaying wakeup times.	7
Kamdar et al. (2004) ^[47]	Obtain as much sleep as possible	7
Leproult et al. (2015) ^[44]	Increase sleep opportunity by 1 hr while following sleep hygiene recommendations	56
Mah et al. (2011) ^[40]	Sleep as much as wanted with a minimum goal of extending sleep opportunity to 10 hr	35–49
Schwartz & Simon (2015) ^[41]	Extend sleep opportunity to 9 hr	7
Stock et al. (2020) ^[46]	Extend sleep opportunity by 1 hr and not nap	7
Swinbourne et al. (2018) ^[42]	Extend sleep opportunity to 10 hr	17
Tasali et al. (2014) ^[45]	Extend sleep opportunity to 8.5 hr	14

Table 3

Means and Standard Deviations of Sleep Variables for Between-Subject Effects

	Sleep duration – actigraphy (hr)		Sleep duration – sleep diary (hr)		Sleep opportunity (hr)		Sleep efficiency (%)		Sleep quality		Daytime sleepiness	
	HAB _B	EXT _B	HAB _B	EXT _B	HAB _B	EXT _B	HAB _B	EXT _B	HAB _B	EXT _B	HAB _B	EXT _B
Al Khatib et al. (2018) ^[31]	5.70 (-)	5.82 (-)	-	-	7.12 (-)	7.97 (-)	80.70 (-)	80.80 (-)	7.10 (-) ⁺	4.10 (-) ^{*+}	-	-
Casement et al. (2020) ^[32]	6.60 (0.45)	7.62 (0.41)*	7.23 (0.49)	8.37 (0.56)*	-	-	89.31 (1.65)	87.28 (2.92)	3.66 (0.44)	3.96 (0.49)	8.95 (3.50)	6.27 (3.38)
Frye (2017) ^[33]	8.12 (0.71)	8.53 (0.89)*	-	-	8.54 (0.80)	9.01 (0.87)*	86.00 (8.30)	86.10 (4.50)	-	-	-	-

Note. EXT_B, extended sleep in between-subject designs. HAB_B, habitual sleep in within-subject designs. *, statistically significant differences between reported means/standard deviations. ⁺, reverse-scored where higher scores indicate less sleep quality. “-”, information is not provided in the original report.

Table 4

Means and Standard Deviations of Sleep Variables for Within-Subject Effects

	Sleep duration – actigraphy (hr)		Sleep duration – sleep diary (hr)		Sleep opportunity (hr)		Sleep efficiency (%)		Sleep quality		Daytime sleepiness	
	HAB _w	EXT _w	HAB _w	EXT _w	HAB _w	EXT _w	HAB _w	EXT _w	HAB _w	EXT _w	HAB _w	EXT _w
Adolescence (n=7)												
Becker et al. (2019) ^[35]	6.55 (0.85)	7.58 (0.71)*	7.12 (0.83)	8.66 (0.67)*	-	-	92.48 (5.00)	90.25 (6.26)*	-	-	-	-
Beebe et al. (2008) ^[38]	7.60 (1.20)	8.70 (1.40)*	7.10 (1.20)	9.30 (0.60)*	-	-	85.00 (14.00)	84.00 (12.00)	-	-	2.70 (2.20)	1.70 (1.80)*
Beebe et al. (2017) ^[36]	6.50 (0.72)	8.08 (1.07)*	-	-	-	-	92.00 (5.00)	89.00 (7.00)*	-	-	-	-
Frye (2017) ^[33]	8.09 (0.69)	8.53 (0.89)*	-	-	8.56 (0.62)	9.01 (0.87)*	86.60 (3.20)	86.10 (4.50)	-	-	-	-
Meltzer et al. (2015) ^[34]	7.49 (0.65)	8.54 (0.44)*	-	-	8.42 (0.48)	9.95 (0.14)*	88.90 (4.40)	85.80 (4.40)	-	-	-	-
Meltzer et al. (2020) ^[39]	7.20 (0.78)	7.78 (0.81)*	-	-	8.21 (0.47)	9.38 (0.24)*	88.00 (7.00)	83.00 (8.00)*	-	-	-	-
Van Dyk et al. (2017) ^[37]	6.16 (0.59)	7.37 (0.59)*	-	-	-	-	95.10 (4.26)	93.90 (4.26)*	-	-	9.00 (2.94)	7.60 (2.94)*
Young Adulthood (n=10)												
Al Khatib et al. (2018) ^[31]	5.47 (-)	5.82 (-)	-	-	7.05 (-)	7.97 (-)	86.20 (-)	80.80 (-)	5.20 (-) ⁺	4.10 (-) ⁺	-	-
Casement et al. (2020) ^[32]	6.47 (0.50)	7.62 (0.41)*	6.96 (0.50)	8.37 (0.56)*	-	-	88.41 (3.75)	87.28 (2.92)	3.80 (0.46)	3.96 (0.49)	6.82 (4.00)	6.27 (3.38)
Famodu (2014) ^[43]	7.16 (0.64)	7.52 (0.75)*	-	-	7.76 (0.80)	8.04 (0.85)	91.7 (3.2)	92.1 (2.5)	-	-	-	-
Kamdar et al. (2004) ^[47]	7.02 (0.88)	8.93 (0.82)*	7.45 (0.58)	9.48 (0.95)*	-	-	-	-	-	-	-	-
Leproult et al. (2015) ^[44]	5.98 (0.48)	6.72 (-)	6.30 (0.50)	7.50 (0.70)*	-	-	-	-	3.60 (0.70)	3.90 (0.70)	-	-
Mah et al. (2011) ^[40]	6.68 (1.03)	8.46 (1.31)*	7.83 (1.10)	10.40 (1.14)*	-	-	-	-	-	-	9.64 (3.80)	3.36 (1.69)*
Schwartz & Simon (2015) ^[41]	-	-	7.14 (0.87)	8.85 (0.60)*	-	-	-	-	-	-	12.15 (4.20)	5.67 (2.46)*
Stock et al. (2020) ^[46]	7.31 (0.67)	8.04 (0.66)*	-	-	-	-	91.00 (2.60)	90.40 (2.90)	-	-	8.80 (4.00)	7.10 (3.40)*
Swinbourne et al. (2018) ^[42]	6.52 (0.93)	7.04 (0.64)*	-	-	8.60 (0.78)	8.82 (0.64)	75.00 (6.70)	79.90 (5.50)*	5.10 (2.20) ⁺	4.90 (1.80) ⁺	6.70 (3.50)	7.00 (4.40)
Tasali et al. (2014) ^[45]	5.60 (0.32)	7.10 (0.32)*	-	-	6.40 (0.63)	8.20 (0.32)*	86.50 (4.43)	86.50 (4.11)	-	-	6.90 (2.85)	2.40 (2.53)*

Note. EXT_w, extended sleep in within-subject designs. HAB_w, habitual sleep in within-subject designs. *, statistically significant differences between reported means/SDs. ⁺, reverse-scored where higher scores indicate less sleep quality. “-”, information is not provided in the original report.

Table 5

Effect Sizes, Confidence Intervals, and Z-scores for Between-Subject Effects

	Sleep duration – actigraphy (hr)		Sleep duration – sleep diary (hr)		Sleep opportunity (hr)		Sleep efficiency (%)		Sleep quality		Daytime sleepiness	
	ES (95% CI)	z	ES (95% CI)	z	ES (95% CI)	z	ES (95% CI)	z	ES (95% CI)	z	ES (95% CI)	z
Al Khatib et al. (2018) ^[31]	0.91 (0.28–1.55)	2.81	-	-	1.39 (0.72–2.07)	4.05	-0.95 (-1.59–(-0.31))	-2.91	0.83 (0.20–1.46)	2.57	-	-
Casement et al. (2020) ^[32]	2.38 (1.26–3.49)	4.17	2.17 (1.11–3.22)	4.03	-	-	-0.86 (-1.73–0.02)	-1.92	0.64 (-0.21–1.5)	1.47	-0.78 (-1.65–0.09)	-1.76
Frye (2017) ^[33]	0.52 (0.13–0.91)	2.63	-	-	0.56 (0.17–0.95)	2.84	0.01 (-0.37–0.4)	0.08	-	-	-	-
Combined	0.77 (0.45–1.09)	4.74	2.17 (1.11–3.22)	4.03	0.77 (0.43–1.11)	4.48	-0.31 (-0.62–(-0.01))	-2.01	0.76 (0.25–1.27)	2.94	-0.78 (-1.65–0.09)	-1.76

Note. CI = confidence interval; ES = effect size; z = z-score. [†] effect sizes were calculated based on the change from pre-intervention baseline because the original report did not provide sufficient post-intervention statistics. “-”, information is not provided in the original report. 0.01, very small effects; 0.20, small effects; 0.50, moderate effects; 0.80, large effects; 1.20, very large effects; 2.00, huge effects.

Table 6
Effect Sizes, Confidence Intervals, and Z-scores for Within-Subject Effects

	Sleep duration – actigraphy (hr)		Sleep duration – sleep diary (hr)		Sleep opportunity (hr)		Sleep efficiency (%)		Sleep quality		Daytime sleepiness	
	ES (95% CI)	z	ES (95% CI)	z	ES (95% CI)	z	ES (95% CI)	z	ES (95% CI)	z	ES (95% CI)	z
Adolescence (n=7)												
Becker et al. (2019) ^[35]	1.32 (1.01–1.62)	8.37	2.04 (1.58–2.50)	8.70	-	-	-0.39 (-0.56–(-0.23))	-4.59	-	-	-	-
Beebe et al. (2008) ^[38]	0.84 (0.47–1.21)	4.47	2.32 (1.51–3.13)	5.61	-	-	-0.08 (-0.33–0.18)	-0.59	-	-	-0.50 (-0.87–(-0.12))	-2.59
Beebe et al. (2017) ^[36]	1.73 (1.45–2.02)	11.98	-	-	-	-	-0.49 (-0.63–(-0.35))	-6.92	-	-	-	-
Frye (2017) ^[33]	0.56 (0.37–0.75)	5.72	-	-	0.59 (0.40–0.79)	5.95	-0.13 (-0.29–0.03)	-1.58	-	-	-	-
Meltzer et al. (2015) ^[34]	1.90 (1.00–2.81)	4.12	-	-	4.29 (2.38–6.20)	4.40	-0.70 (-1.17–(-0.24))	-2.96	-	-	-	-
Meltzer et al. (2020) ^[39]	0.73 (0.53–0.93)	7.00	-	-	3.14 (2.53–3.75)	10.07	-0.67 (-0.86–(-0.47))	-6.64	-	-	-	-
Van Dyk et al. (2017) ^[37]	2.06 (1.64–2.47)	9.69	-	-	-	-	-0.28 (-0.44–(-0.12))	-3.45	-	-	-0.48 (-0.70–(-0.25))	-4.20
Young Adulthood (n=10)												
Al Khatib et al. (2018) ^[31]	-	-	-	-	-	-	-	-	-	-	-	-
Casement et al. (2020) ^[32]	2.52 (1.41–3.62)	4.47	2.66 (1.46–3.85)	4.36	-	-	-0.34 (-0.7–0.03)	-1.82	0.34 (-0.14–0.82)	1.38	-0.15 (-0.51–0.21)	-0.81
Famodu (2014) ^[43]	0.53 (0.26–0.79)	3.92	-	-	0.34 (0.05–0.63)	2.33	0.14 (-0.11–0.38)	1.11	-	-	-	-
Kamdar et al. (2004) ^[47]	2.25 (1.29–3.22)	4.57	2.58 (1.60–3.56)	5.17	-	-	-	-	-	-	-	-
Leproult et al. (2015) ^[44]	-	-	1.97 (1.22–2.72)	5.15	-	-	-	-	0.43 (0.02–0.84)	2.06	-	-
Mah et al. (2011) ^[40]	1.51 (0.80–2.23)	4.15	2.30 (1.27–3.33)	4.37	-	-	-	-	-	-	-2.14 (-3.10–(-1.18))	-4.36
Schwartz & Simon (2015) ^[41]	-	-	2.29 (1.31–3.27)	4.56	-	-	-	-	-	-	-1.88 (-2.71–(-1.06))	-4.47
Stock et al. (2020) ^[46]	1.10 (0.84–1.35)	8.32	-	-	-	-	-0.22 (-0.38–(-0.06))	-2.71	-	-	-0.46 (-0.64–(-0.27))	-4.89
Swinbourne et al. (2018) ^[42]	0.66 (0.37–0.94)	4.48	-	-	0.31 (0.07–0.55)	2.56	0.80 (0.49–1.11)	5.00	0.10 (-0.21–0.4)	0.64	0.08 (-0.16–0.31)	0.3
Tasali et al. (2014) ^[45]	4.74 (2.64–6.85)	4.41	-	-	3.60 (1.98–5.22)	4.37	0.00 (-0.35–0.35)	0.00	-	-	-1.67 (-2.49–(-0.85))	-3.99
Combined	0.97 (0.89–1.06)	21.90	2.19 (1.90–2.49)	14.74	0.61 (0.48–0.74)	9.20	-0.26 (-0.32–(-0.21))	-8.90	0.24 (0.02–0.46)	2.18	-0.39 (-0.50–(-0.29))	-7.18

Note. CI = confidence interval; ES = effect size; z = z-score. “-”, information is not provided in the original report. 0.01, very small effects; 0.20, small effects; 0.50, moderate effects; 0.80, large effects; 1.20, very large effects; 2.00, huge effects.