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ORIGINAL ARTICLE

SLEEP DEFICITS AND EXECUTIVE FUNCTIONS AT DIFFERENT DEVELOPMENTAL STAGES - META-ANALYSIS

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Introduction: The aim of the article is to present the results of a meta-analysis of the relationship between sleep deficits and executive functions at different stages of human development (school age, young adults, older adults).

Methods: The meta-analysis included 13 studies with a total of 625 participants, of which we extracted 24 comparisons regarding the age group, type of sleep deficiency, studied executive functions and their measurement methods.

Results: Among the studied executive functions, sleep deficiency influenced cognitive shifting but had no relationship with inhibition of reactions or working memory.

Discussion: The discussion focused on the differential influence of partial chronic sleep deficits, in comparison to a single instance of total sleep deficit, on executive functions.

Conclusions: This meta-analysis supports the need to conduct further research on the influence of lack of sleep on executive functions in larger studies and in participants at different stages of development.

Keywords: sleep deficit, executive function, cognitive flexibility, inhibition, meta-analysis

Figure: 1 • **Table:** 1 • **Charts:** 5 • **References:** 62 • **Full-text PDF:** http://www.pjambp.com • **Copyright** © 2016 Polish Aviation Medicine Society, ul. Krasińskiego 54/56, 01-755 Warsaw, license WIML • **Indexation:** Index Copernicus, Polish Ministry of Science and Higher Education

INTRODUCTION

Sleep is an important process that regenerates and rebuilds the organism; it is essential for normal cognitive, emotional and social development. The subject matter of sleep is often viewed from a clinical standpoint; researchers are interested in qualitative and quantitative sleep disorders and their consequences for psychological functioning of people. At the same time, there are studies carried out within the developmental paradigm that are aimed at determining the role of sleep in the life cycle and how the lack of sleep influences the development at any given developmental stage.

The number of hours that are reserved for sleeping has been steadily decreasing, and this can be also observed in children [14,22,32]. Approximately 15-30% of children aged 2-5 years experience sleep difficulties [31]. The amount of sleep in this age group depends primarily on the cultural and social factors, e.g. a habit of napping in the nursery [24]. After the fifth year of age, the quality of sleep worsens because of nightmares that disturb sleeping [2]. In school-aged children, the percentage of children with sleep disorder falls to 11-15% [33]. However, over 25% of students in secondary schools in the United States do not get enough sleep [59].

Throughout the life cycle, both the quality and time of sleep change [12]. People aged 65 to 75 years wake up 1.33 hours earlier and fall asleep 1.07 hours earlier than people aged 2 to 30 years [18]. In these people, insomnia associated with other diseases of the old age is more common [60]. Similarly, they also suffer more frequently from other conditions that disturb sleeping such as restless leg syndrome or sleep apnea. Therefore, they more often feel the need to get additional sleep during the day [36].

The character of sleep changes with age. From the moment of birth to late adulthood, there are changes in sleep initiation, sleep maintenance, proportions of sleep spent in different sleep phases and effectiveness of sleep [8]. For instance, the estimated time of falling asleep and wake time after sleep onset (WASO) decreases from 550 minutes just after birth to 320-420 minutes at the age of 85 years. After 60 years of age, the stage of deep sleep, during which intense regenerative processes take place, is decreased. After 85 years of age, the amount of REM sleep decreases from 420-550 minutes, seen after birth, to 250-320 minutes. [60].

Consequences of sleep deprivation – neuropsychological perspective

With age, the physiological (e.g. neurochemical) processes of sleep and falling asleep change, which can lead to sleep disorders. Lack of sleep can be total (total sleep deprivation) when the organism has been in a single, long-term state of wakefulness (more than 16 hours) [46]. Many cortical and subcortical areas are susceptible to even minor sleep deficits [6]. The experiments carried out by Thomas et al. [46] with the use of positon emission tomography showed that during a 24-hour period of sleep deprivation the glucose metabolism in globally decreased in the brain. Moreover, a decreased functional connection between the medial frontal cortex and the amygdala was shown, which can result in disruption of behavioral and emotional regulation [61].

Lack of sleep also worsens brain neuroplasticity which is required for its adaptive capabilities that are the basis for self-repair, learning and memory. Experiments performed in rats [19] have shown that a 96-hour sleep deprivation results in a 50% decrease in the generation of new neurons in the dentate gyrus of the hippocampus which is involved in formation of new memory traces.

The current lifestyle is associated with shift work, long working hours and exposition of the eyes to short-wave light during the night (emitted e.g. by television screens, computers, lightning), all of which inhibit the production of melatonin by the pineal gland and resulting in sleep restriction, i.e. sleep times that are inadequate for individual people [8]. According to current data, 20% of adults in the United States sleep less than 6.5 hour a day [28], which can result in day sleepiness over the next 4 days [3], increasing fatigability, disorientation, tension, mental exhaustion and stress [13].

Sleep deficit that has accumulated over several days causes changes in cognitive function [51]. Day-today sleep deficit is also associated with increasing stress levels and dysregulation of serotonin reuptake [41], increased activity of the sympathetic nervous system [27] and disturbances of glucose metabolism [40].

Prefrontal cortex (PFC) is a brain region that is exceptionally susceptible to sleep deficits. During wakefulness, this area is the most active cerebral cortex region of the brain that is associated with a broad range of cognitive functions [9], and it is regenerated during sleep. Even short sleep deficits can disturb the function of PFC, which in consequence leads to disorders of attention and divergent thinking [57], disorders of speech [17], difficulties in making decisions, disorders of memory and inhibition of reactions [20].

Sleep deficit and effectiveness of executive functions

Cognitive processes are controlled and managed by executive functions (EF) that are localized in the above-mentioned area of PFC [25]. They are associated with a broad range of cognitive processes and abilities relevant for an efficacious engagement in conscious, voluntary, planned and intentional behaviors [30]. Decreased function of these areas is often associated with dysfunction of the prefrontal cortex [43]. As a result of sleep deficit, PFC decreases its activity, which leads to depressed executive functioning.

Based on a meta-analysis performed over two decades ago that included 143 comparisons from 19 studies, sleep deficits lead to a decreased cognitive task performance [37]. Studies performed in school-aged children have shown that partial sleep deficit decreases attention and working memory function [53]. Experiments with adults have confirmed that partial sleep deficit decreases performance of tasks requiring cognitive control – both in early and middle adulthood [44,45].

In this article, we analyzed the current state of knowledge on the influence of different sleep deficits, caused by a prolonged activity of various durations, on executive function in different age groups. In order to objectify the compared study results, we focused on the three most commonly described executive functions. We made use of the A.F. Kiyake's model that differentiates (1) shifting, (2) updating and monitoring of working memory representation and (3) inhibition.

METHODS

Selection of studies

In order to perform this meta-analysis, we searched the GoogleScholar and EBSCOhost databases with regard to randomized studies dealing with the relationship between sleep deprivation (total or partial) and cognitive function. We also searched the databases of journals that publish articles in this field of study – e.g. Sleep Medicine, Sleep, Sleep Medicine Review, Journal of Sleep Research. We used the following search terms - "sleep deprivation" and "executive function". We took into consideration only full-text articles. We excluded articles that were available only as abstracts. Moreover, in the process of article selection, we took into consideration the references of selected articles including both empirical studies and reviews in the relevant field of study.

Below, we present the basic inclusion criteria:

1) Studies that assessed at least one of the above-mentioned executive functions:
   1.1. Inhibition – defined as a "complete stopping of a competing tendency to react, while in the period directly preceding an intentionally delayed response, various manipulations in the systems of cognitive representations are carried out" [26, p. 252].
   1.2. Supervising and integrating function of working memory – allowing for monitoring and storing information in memory as well as for rational division of cognitive resources [35].
   1.3. Shifting – defined as divided attention [4].
2) Studies that employed the common methods and paradigms of executive function measurement, i.e.:
   2.1. Inhibition of reaction - Stroop's test or Go/No Go Task [34].
   2.2. Supervising and integrating function of working memory- Sternberg's task [47].
   2.3. Shifting - task-switching paradigm [23].
3) Studies that described the type of sleep deficit:
   3.1. WASO (Wake Time After Sleep Onset) – time of intermittent wakefulness, i.e. sleep latency and time of wakefulness after waking someone's up after they have fallen asleep.
   3.2. Sleep reduction – everyday shortening of sleep duration by a specific time period with the minimal period of sleep reduction of 30 minutes.
   3.3. Total deficit – sleep deprivation of 24 to 51 hours with the preservation of constant routine in which participants performed specific cognitive tasks at predefined intervals.
4) Studies carried out in healthy participants without clinical groups, children with special educational needs or people with mental disabilities.

Additional criteria that were essential for determining the studied groups were as follows:

– information on the number of participants (min. 8 and max. 99, see Table 1),
– randomized allocation to experimental and control groups and number of participants in each group,
– complete information regarding the studied groups (age, gender, education, method of recruitment) and precisely described experimental procedure.

We evaluated the results of studies that compared the above-mentioned executive functions (shifting, inhibition, working memory) between groups with sleep deficit (total or partial) that was expressed in the number of hours and control groups without sleep deficit.

Fig. 1. Selection of studies for meta-analysis.

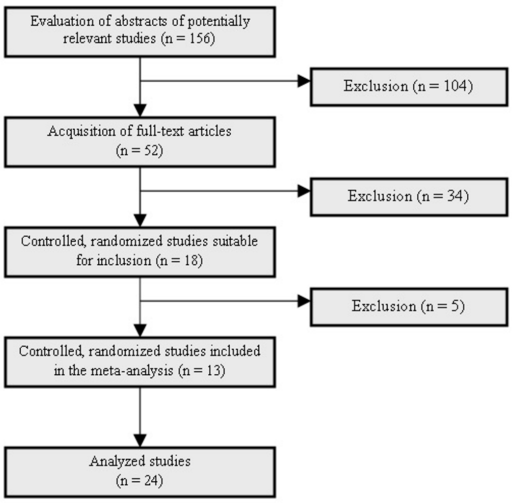


Figure 1 presents the process of searching for and selecting studies. The first step in was an evaluation of abstracts. We included 156 studies that were evaluated with regard to the above-mentioned criteria. Of the 156 abstracts, we excluded 104 because of the lack of availability of full-text articles. Therefore, for further selection, 52 articles were included.

After obtaining full-text articles, the next step of selection involved an evaluation of experimental groups. We excluded 34 studies that investigated clinical groups (qualitative and quantitative sleep disorders, psychiatric diseases, specific educational needs, mental disability, other diseases), neuroimaging studies and studies written in languages other than English. Of the remaining 18 articles, 5 were excluded due to insufficient data, and 13 articles were included in the final analysis.

Characteristics of studies

Table 1 presents characteristics of the 13 analyzed studies. A total of 625 participants was included.

Of the total number of participants, women comprised 36-73% of participants and men 27-100%, respectively. Two studies did not include women and two other studies did not disclose information on the gender of participants. The mean age ranged between 9.8 and 68 years, which reflects a broad range of age of participants.

The greatest number of studies were carried out in North America; four studies in the United States and one study in Canada. Three studies were performed in Asia; two in China and one in Israel. Three studies were performed in Europe; one study in France, Sweden and Italy each. Another two studies were carried out in Australia. This reflects the fact that participants included in this meta-analysis were culturally diverse.

The studies included in this meta-analysis different substantially in terms of quality (type of executive functions and their measurement) and quantity (study sample sizes). Because of that, we analyzed 18 studies that compared experimental and control groups. (see Tab. 1).

Moreover, comparisons were also made with regard to:

1. Age of participants:
   1.1. School-aged children (M = 9.8 – M = 14.9 years), 5 studies.
   1.2. Young adults (M =19 – M = 30 years), 14 studies.
   1.3. Older adults (M = 62.68 – M = 68 years), 5 studies.
2. Type of executive function:
   2.1. Shifting, 3 studies.
   2.2. Inhibition, 13 studies.
   2.3. Working memory, 8 studies.
3. Type of sleep deprivation:
   3.1. WASO, 6 studies.
   3.2. Sleep reduction, 7 studies.
   3.3. Total deprivation, 11 studies.

Data analysis

We analyzed the results of cognitive tests obtained at the end of extended activity, regardless of its duration. For the purposes of simplicity, studies that compared different age groups and different executive functions were treated as separate studies and were marked with consecutive alphabet letters.

The procedure described by J. Cohen [7] was used to investigate the influence of sleep deprivation on executive function. Based on data provided by authors of the respective studies, such as means, standard deviations, correlations, regression coefficients, F statistics, we calculated effect size (Cohen's d) with the use of an internet calculator (available at www.campbellcollaboration.org). The mean effect size with a 95% confidence interval (CI) was calculated with the I.O. Hedges's method [21]. We employed random-effects proce-

Tab. 1. Weight and description of studies included in the meta-analysis.

Study	Country[1]	N[2]	No[3]	Gender[4]	Age group	Education	Type of EF	EF measurement method	Type of sleep deprivation	w5	p6
Cain. et al., 2011	USA	30		36.7/63.3	young adults	secondary, in the course of studies	inhibition	stroop's task	sleep deprivation (40h)	5.44%	0.02
Couyoumdjian, 2010	Italy	108		73.15/26,8	young adults	secondary, in the course of studies	shifting	task-switching paradigm	sleep deprivation (24h)	4.62%	0.03
Gradisar et al., 2008	Australia	23	[a]	57/43	school age	pupils of primary schools	working memory	LNS (letter-number sequencing)	sleep reduction	11.18%	0.01
		23	[b]	57/43	school age	pupils of primary schools	working memory	Op Span (operation span task)	sleep reduction	11.24%	0.01
Nilsson et al., 2005	Sweden	22	[a]	-	young adults	secondary, in the course of studies	inhibition	SET (Six Element Test)	sleep deprivation (31h)	1.90%	0.01
		22	[b]	-	young adults	secondary, in the course of studies	working memory	CD (The Claeson Dahl)	sleep deprivation (31h)	1.99%	0.01
Qi et al., 2010	People's Republic of China	40		0/100	young adults	secondary, in the course of studies	inhibition	go/ no go task	sleep deprivation (43h)	1.76%	0.02
		40									
Rossa et al., 2013	Australia	20	[a]	60/40	young adults	secondary, in the course of studies	inhibition	go/ no go task	sleep reduction	1.85%	0.01
		20	[b]	60/40	young adults	secondary, in the course of studies	inhibition	BART (balloon analog risk task)	sleep reduction	1.78%	0.02
Sadeh et al., 2003	Israel	77	[a]	50.7/49.3	school age	pupils of primary schools	inhibition	continuous performance test	sleep reduction	7.16%	0.01
		77	[b]	50.7/49.3	school age		working memory	visual digit span test	sleep reduction	7.17%	0.01
Segaspe et al., 2012	France	25	[a]	0/100	young adults	secondary, in the course of studies	inhibition	simple reaction time task	sleep deprivation (40h)	2.25%	<0.01
			[b]	0/100	young adults	secondary, in the course of studies	inhibition	go/ no go task	sleep deprivation (40h)	2.53%	<0.01
			[c]	0/100	older adults	no information	inhibition	simple reaction time task	sleep deprivation (40h)	2.06%	0.01
			[d]	0/100	older adults	no information	inhibition	go/ no go task	sleep deprivation (40h)	1.98%	0.02
Shao et al., 2009	People's Republic of China	14		0/100	young adults	secondary, in the course of studies	inhibition	go/ no go task	sleep deprivation (36h)	2.60%	0.01
Tucker et al., 2009	USA	23		47.8/52.2	young adults	secondary, in the course of studies	working memory	sternberg's task	sleep deprivation (51h)	1.51%	0.02
Vriend et al., 2013	Canada	32		56.2/43.8	school age	pupils of secondary schools	working memory	visual digit span test	sleep reduction	2.92%	0.02
[1] Wilckens et al., 2014	USA	99	[1a]	67.8/32.2	young adults	secondary, in the course of studies	shifting	task-switching paradigm	WASO	4.43%	0.02
			[1b]	71.1/28.9	older adults	at least secondary	shifting	task-switching paradigm	WASO	4.06%	0.02
[2] Wilckens et al., 2014	USA	112	[2a]	-	young adults	secondary, in the course of studies	inhibition	stroop's task	WASO	5.29%	0.02
			[2b]	-	young adults	secondary, in the course of studies	working memory	sternberg's task	WASO	4.65%	0.02
			[2c]	-	older adults	secondary	inhibition	stroop's task	WASO	4.73%	0.02
			[2d]	-	older adults	secondary	working memory	sternberg's task	WASO	4.92%	0.01

Note: 1 country in which the study was performed; 2 number of studied participants (in the experimental and control groups together) in each age group; 3 consecutive numbers of studies in a given article; 4 female-to-male ratio; 5 weight of the study in the model; 6 significance of the study in the model.

1 - Evaluation of abstracts of potentially relevant studies (n = 156); 2 - Acquisition of full-text articles (n = 52); 3 - Controlled, randomized studies suitable for inclusion (n = 18); 4 - Controlled, randomized studies included in the meta-analysis (n = 13); 5 - Analyzed studies (n = 24).

dures and therefore variance between studies was estimated with TAU2 and Cochran's Q. The analysis was performed with Open Meta-Analyst software [52,54].

RESULTS

The analyzed set of studies was valid for the assessment of effect size of all studies (tau2 = .88; Q(23) = 184.189; p < .001; I2= 90.57). Based on 95% confidence intervals, a significant effect was noted in 7 out of 24 studies.

The general effect size was 0.51 (95% CI = 0.11–0.91), p = .01. Because of that, the weighted mean of all studies is within the interval for the mean effect (Cohen's d =0.43-0.69).

Validation of the model with the use of the LOO procedure (leave one out) determined that the influence of all studies was balanced.

As can be seen on Chart 2, the studies by Cain et al. [5] and Qi et al. [39] differ most substantially from the mean effect size and decrease it.

The analysis performed in age sub-groups revealed that there were no significant differences in the sub-group means (omnibus p = 0.54). Studies that included children did not show that sleep had a significant influence on executive functions, and the weighted mean of the effect size was 15 (CI 95% = -0.04–0.34; p = 0.12). The mean effect size of 68 (CI 95% = 0.00–1.36; p = 0.05), found in studies with young adults, was on the verge of statistical significance. However, in studies with older adults, the mean effect size of the impact of sleep deficit on executive function was 0.41 and was significant (CI 95% = 0.13–0.70; p <0 .01).

The meta-analysis also determined that, in the analyzed studies, sleep deprivation was significantly associated only with deceased shifting – the weighted mean of the effect size was 1.55 (CI 95% = 0.03–3.08; p <0.05), which indicates a large effect. Inhibition (the weighted mean of effect size of 0.31; CI 95% = -0.23–0.85; p = 0.26) and working memory (the weighted mean of 0.41; CI 95% = -0.10–0.93; p = 0.11) were not associated with sleep deprivation (see Chart 4). The results obtained in the three types of executive functions did not differ significantly (omnibus p = 0.06).

The analysis also showed that the choice of the method of measurement of sleep deprivation (total vs. partial) did not differentiate between the obtained results (omnibus p = 0.65). In the sub-group of studies with total sleep deprivation (24-48 h), the mean effect size was insignificant (the weighted mean effect size of 0.57; CI 95% = -0.30 – 1.44; p = 0.20). Moreover, meta-regression analysis did not reveal any association between the number of sleep deprivation and executive functions (p = 0.95). However, this result can be due to a low number of included studies (n = 10).

In the sub-group of "sleep reduction", a low level of effect size of 0.17 was on the verge of statistical significance (CI 95% = -0.01–0.36; p = 0.06). The effect of sleep deprivation was

Chart 1. Influence of sleep deficit on executive functions in different age groups.

Studies	Estimate (95% C.I.)
Cain. i in. 2011	0.503 (−0.011, 1.017)
Couyoumdjian 2010	3.078 (2.521, 3.635)
Gradisal i in. [a] 2008	0.221 (−0.137, 0.579)
Gradisal i in. [b] 2008	0.000 (−0.357, 0.357)
Nilsson. i in. [a] 2005	−0.808 (−1.677, 0.061)
Nilsson. i in. [b] 2005	−0.525 (−1.375, 0.325)
Qi i in. 2010	2.999 (2.096, 3.902)
Rossa i in. [a] 2013	0.261 (−0.619, 1.141)
Rossa i in. [b] 2013	0.633 (−0.265, 1.531)
Sadeh i in. [a] 2003	0.166 (−0.282, 0.613)
Sadeh i in. [b] 2003	0.143 (−0.304, 0.591)
Segaspe. i in. [a] 2012	−1.149 (−1.948, −0.349)
Segaspe. i in. [b] 2012	−0.519 (−1.272, 0.234)
Segaspe. i in. [c] 2012	0.000 (−0.836, 0.836)
Segaspe. i in. [d] 2012	0.569 (−0.284, 1.421)
Shao i in. 2009	0.242 (−0.502, 0.985)
Tucker i in. 2009	1.844 (0.867, 2.820)
Vriend i in. 2013	0.430 (−0.271, 1.131)
Wilckens i in. [1a] 2014	1.052 (0.483, 1.621)
Wilckens i in. [1b] 2014	0.524 (−0.070, 1.118)
Wilckens i in. [2a] 2014	0.579 (0.058, 1.100)
Wilckens i in. [2b] 2014	1.220 (0.664, 1.776)
Wilckens i in. [2c] 2014	0.613 (0.062, 1.164)
Wilckens i in. [2d] 2014	0.244 (−0.297, 0.784)
Overall (I^2=90.57 % , P< 0.001)	**0.512 (0.112, 0.912)**

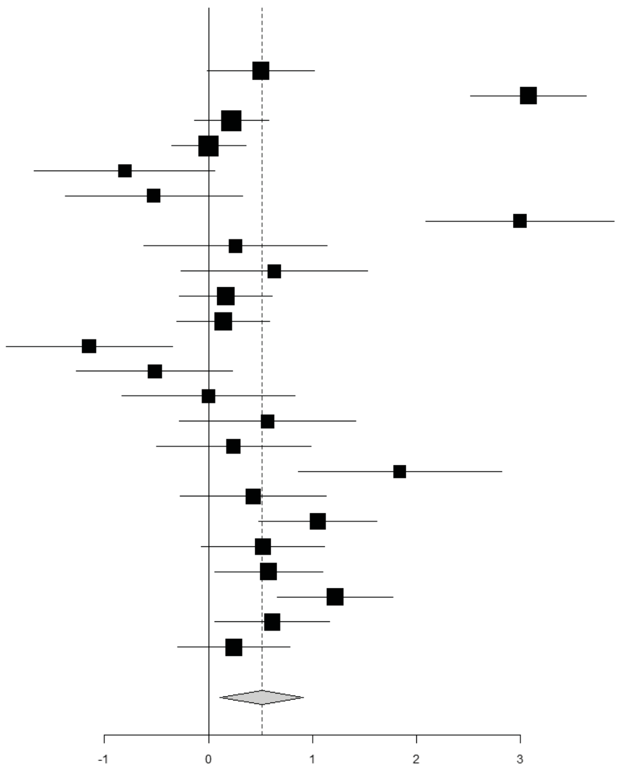


Chart 2. Model validation with the use of the LOO method.

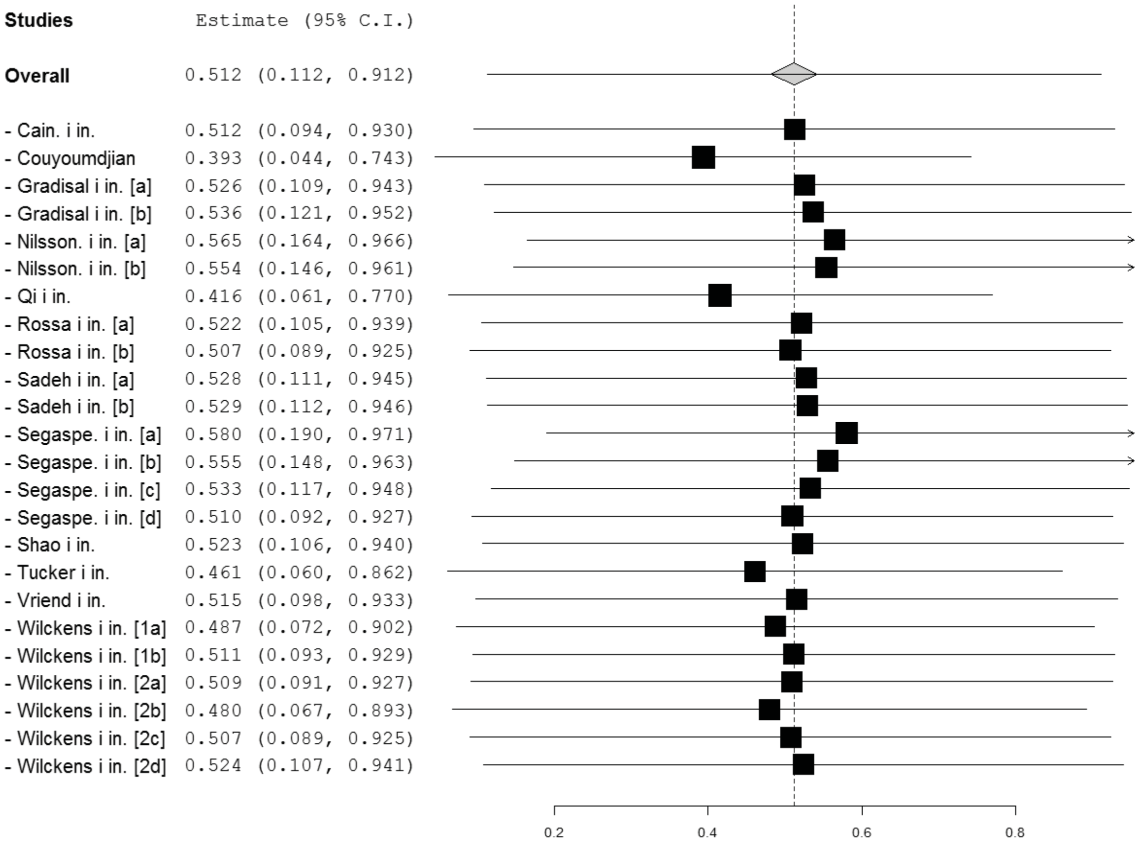


Chart 3. Effect size of the influence of sleep deficit on executive function in school-aged children, young adults and older adults.

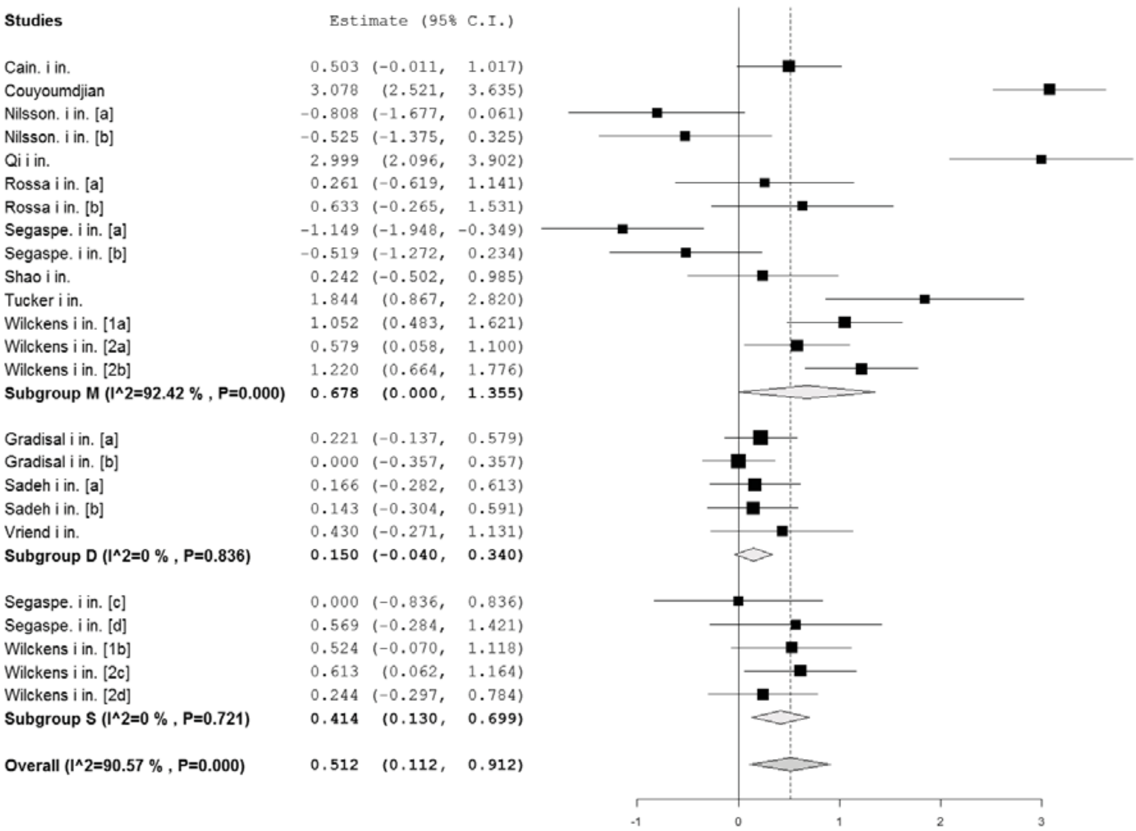


Chart 4. Effect size of the influence of sleep deprivation on inhibition, shifting and working memory in different age groups.

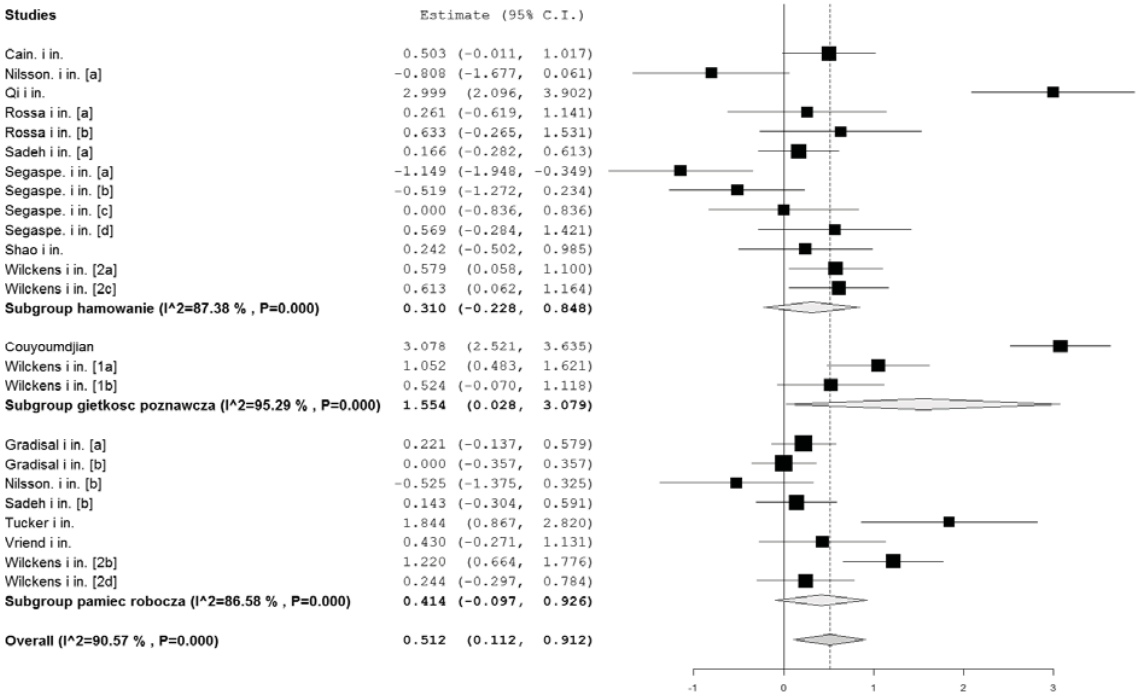
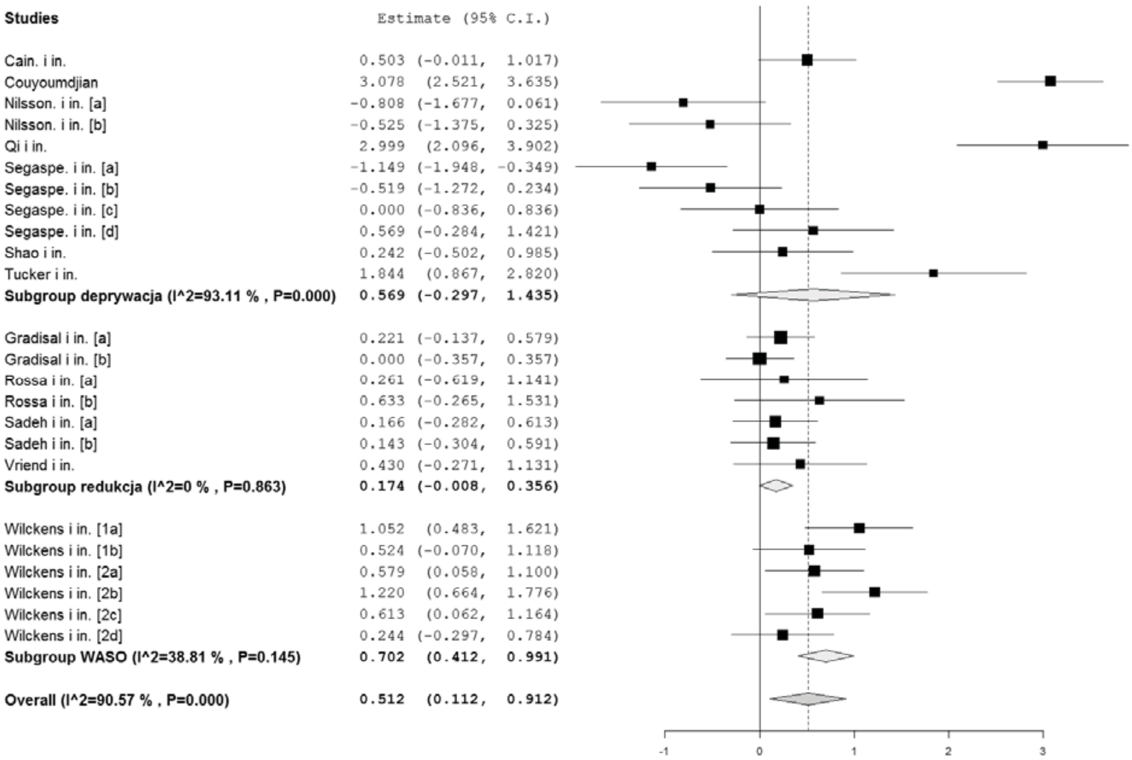


Chart 5. Effect size of the influence of the type of sleep deficit (total deprivation, sleep reduction and WASO) on executive functions in different age groups.



significant in the studies that measured partial sleep deprivation with WASO (see Chart 5). The weighted mean of effect size was 0.70 (CI 95% = 0.41–0.99; $p < 0.001$), which indicates a high level of effect size.

DISCUSSION

The aim of this article was to perform a meta-analysis of the available studies investigating the effect of sleep deficit (total and partial) on executive functions. We anticipated that lack of sleep, to which prefrontal cortex areas are most susceptible, would decrease executive functions in the three following domains – (1) inhibition of reactions, (2) supervision and integration of working memory and (3) shifting. However, this influence was only observed in the case of shifting. On the one hand one can suspect that shifting is more susceptible to sleep deprivation than other executive functions. On the other hand it should be taken into account that in this analysis only three studies were included, which decreases the significance of the result.

We did not find any influence of sleep deprivation on cognitive inhibition or working memory. This conclusion is contrary to many studies performed so far (see Kurdziel, Duclos, Spencer, 2013). Similarly, the state-instability theory underscores the relationship between lack of sleep and disturbances of wakefulness, which decreases attention, working memory and slows down motor reactions [15]. This theory indicates that working memory is especially susceptible to lack of sleep as it is controlled by the processes of attention.

It should be noted that in the majority of included studies the so-called "cool" executive functions and their relationship with sleep were investigated [42]. According to Zelazo and U. Müller [62], "cool" executive functions are engaged in solving relatively abstract problems that are not nested in any context and therefore are insignificant to the individual [38]. "Cool" EF should be differentiated from "hot" EF that are, in turn, engaged during solving problems requiring affective and emotional regulation. Perhaps, "hot" EF are susceptible to sleep deficits, which could be confirmed by studies on the effect of lack of sleep on disturbances of emotional and motivational processes as well as on the processes of decision making [20]. Similar evidence comes from the studies on REM sleep disturbances in school-aged children [53] and in adults [11]. Because disturbances of frontal lobe function that are associated with sleep deficits could to a greater extent impair "hot" EF engaged in affective and motivational processes, in our opinion, further research should focus on the effects of sleep deprivation on these functions (e.g. with the use of the Iowa Gambling Task [1]).

The anticipated effect was not found in all age groups. Based on our analysis, executive functions are more prone to be impaired in the elderly (based on 5 studies). With age, the prevalence of various sleep disorders increases (e.g. primary or secondary insomnia, insomnia related to other diseases of the old age, restless leg syndrome, snoring, sleep apnea), which results in decreased sleep effectiveness [60]. In consequence, this additional sleep deficit can contribute to a decreased cognitive functioning in this age group as compared to younger people who less commonly have sleep disorders.

Contrary to our expectations, we did not observe this effect in school-aged children. It is worth mentioning that, because of ethical and medical reasons, studies investigating sleep deficits are relatively rare in this age group. The studies included in the meta-analysis used only short periods of sleep deficits that did not constitute significant or total sleep deprivation.

Moreover, our meta-analysis determined that total sleep deprivation (at least 24 hours) did not significantly influence executive functions. Despite the fact that this method of sleep control was most commonly applied (in 11 studies), the number of hours of sleep deficit was variable. The lack of a significant effect can also be related to the procedure of constant vigilance. Although the investigators chose experimental tasks so as to minimize the effect of learning, an adaptation to study procedures could still influence the results. In consequence, the results of consecutive tests performed throughout the studies could not necessarily differ from those obtained at the beginning of the procedure. The effect of methods with partial sleep deprivation, in which participants did not perform tests of executive functions so often, was significant (or marginally significant). Moreover, these methods were associated with chronic sleep deprivation and there are studies indicating that this type of sleep deprivation can impair mental function to a greater extent in comparison to a single extension of the period of wakefulness, as the effect is cumulative [51].

It is still not known if sleep deficits impair all cognitive processes equally or if some processes are affected to a greater extent. The tests of EF engage many other cognitive processes (e.g. voluntary attention, perception, language skills), and because of that we can deal with indirect effects of sleep deficits on the function of higher cognitive processes. However, neuroimaging studies indicate that the influence of sleep deprivation on EF is direct, as sleep deprivation is associated with a reduction of metabolic activity in the prefrontal cortex that plays an important role in cognitive control [16].

Our conclusions are also associated with improper reporting of many studies that did not disclose basic information required for carrying out meta-analyses. It is still not known why sleep deficit impairs certain executive functions and does not affect others.

The many questions that are posed by our meta-analysis indicate that there is a need for further research on the effects of sleep deprivation on executive function in larger samples and in participants at different stages of development. There is also a need for a policy of open access to the published studies which could facilitate the process of data gathering in order to make unifying conclusions on the current state of knowledge.

AUTHORS' DECLARATION:

Study Design: Marta Molińska, Agata Złotogórska; **Data Collection:** Marta Molińska, Agata Złotogórska; **Funds Collection:** Marta Molińska, Agata Złotogórska. The Authors declare that there is no conflict of interest.

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