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SHORT REVIEW

Executive Function in Pediatric Sleep-Disordered Breathing: A Meta-analysis

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Abstract

Objectives: Evaluate the association between pediatric sleep-disordered breathing (SDB) and executive functioning. **Methods:** We searched multiple electronic databases for peer-reviewed journal articles related to pediatric SDB and executive functioning. We included studies that assessed SDB *via* polysomnography, included objective or questionnaire measures of executive function, and had an age-matched control group. Fourteen articles met inclusion criteria with a total sample of 1697 children ages 5 to 17 years ($M = 9.81$ years; $SD = 0.34$). We calculated an overall effect size for each of the five executive domains (vigilance, inhibition, working memory, shifting, and generativity) as well as effect sizes according to SDB severity: mild, moderate, severe. We also calculated effect sizes separately for objective and subjective questionnaires of executive functioning. **Results:** We found a medium effect size (–0.427) for just one of five executive function domains on objective neuropsychological measures (generativity). In contrast, effect sizes on all three executive domains measured *via* questionnaire data were significant, with effect sizes ranging from medium (–0.64) to large (–1.06). We found no difference between executive domains by severity of SDB. **Conclusions:** This meta-analysis of executive function separated into five domains in pediatric SDB suggested lower performance in generativity on objective neuropsychological measures. There were no differences associated with SDB severity. Questionnaire data suggested dysfunction across the three executive domains measured (inhibition, working memory, shifting). Overall, limited evidence suggested poorer performance in executive function in children with SDB according to objective testing, and subjective ratings of executive function suggested additional worsened performance. (*JINS*, 2016, *22*, 839–850)

Keywords: Sleep apnea, Snoring, Child, Adolescent, Cognition, Neurobehavioral

INTRODUCTION

Executive functions are considered effortful, top–down processes necessary to attend to important stimuli (Diamond, 2013). While a large number of executive processes have been hypothesized, three overarching classes or subcomponents of executive function are often described: working memory (also referred to as "updating"), inhibitory-control abilities, and set shifting (Miyake et al., 2000). Thus, observed executive functioning abilities tend to be ascribed to one of these three categories (Diamond, 2013; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003). Executive function skills are necessary for social competence, psychological health, physical health, and academic success (Bull, Espy, & Wiebe, 2008; Cartwright, 2012; Duke & Harris, 2014; Ganesalingam et al., 2011; McNamara et al., 2014; Reinert, Po'e, & Barkin, 2013; Riggs, Huh, Chou, Spruijt-Metz, & Pentz, 2012); therefore, deficits in executive abilities in childhood or adolescence may have important implications for daily functioning.

Executive functions begin developing in early childhood and continue to develop into adolescence, and even into adulthood (Zelazo & Carlson, 2012). Executive development in childhood predicts aspects of adult behavior and outcome, including physical health, substance dependence, personal finances, and criminal offending (Moffitt et al., 2011).

A variety of developmental, medical, and psychiatric conditions can affect executive function in children (Yeates, Ris, Taylor, & Pennington, 2010). An estimated 2% to 4% of children experience sleep-disordered breathing (SDB), with up to 17% having nighttime snoring (Rosen et al., 2003).

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Although numerous studies have demonstrated that children who experience SDB, ranging in severity from primary nighttime snoring to obstructive sleep apnea (OSA), may experience neurocognitive dysfunction, not all studies agree, particularly in the context of mild SDB.

For example, although Blunden, Lushington, Kennedy, Martin, and Dawson (2000) reported lower intellectual function, memory, and attention in children diagnosed with SDB compared to a control group and Halbower et al. (2006) found decreases in intellectual function and working memory in SDB, a study with a larger sample size (Calhoun et al., 2009) found no impairment in the mild SDB group on any of the objective neuropsychological measures of executive function. Thus, previous studies regarding the association between executive function and SDB in children have been mixed. Finally, in addition to objective neuropsychological measures, some studies have used validated questionnaires to measure the neurobehavioral symptoms associated with SDB. One such study found that regardless of severity, SDB was associated with parent-reported executive dysfunction (Bourke et al., 2011a).

Beebe and Gozal (2002) hypothesize that the cognitive and behavioral symptoms associated with SDB are likely related to two distinct mechanisms. First, SDB can lead to significant sleep disruption (e.g., sleep fragmentation) that interferes with restorative sleep processes and cellular homeostasis of the prefrontal cortex. Second, apneic or hypopneic events that result in hypoxemia may also disrupt restorative sleep processes and cellular homeostasis. Therefore, the sleep disruption and intermittent hypoxic episodes associated with pediatric SDB have been suggested to affect prefrontal cortical functioning. The cognitive domain most closely associated with this brain region is executive function.

We selected executive-function domains based on previous research including studies involving SDB. In their meta-analysis of the association between OSA and executive function in adults, Olaithe and Bucks (2013) categorized executive function into shifting, updating (working memory), inhibition, generativity, and fluid-reasoning domains. The domain of generativity essentially relates to the ability to access information from long-term memory and has been shown to be dissociable from the other components of executive function. It is also referred to as "access" (Adrover-Roig, Sese, Barcelo, & Palmer, 2012). In this study, we use the term "generativity" as used by Olaithe and Bucks (2013), and we generally adhere to the model of executive functioning they incorporated with a few exceptions. First, we used tests similar to those that Olaithe and Bucks (2013) included for the updating component (digit span, and N-back tasks) but refer to these abilities as working memory as has been done elsewhere (Adrover-Roig et al., 2012). Second, we do not present a fluid-reasoning component in the current meta-analysis because the measures Olaithe and Bucks (2013) included in this domain were often not available in the studies included in our analysis.

Lastly, and in contrast to Olaithe and Bucks (2013), we included vigilance as an executive function component in our analyses for the following reasons. First, a recent meta-analytic review examining the executive function theory of ADHD supported the notion that measures of vigilance are in fact measuring a component of executive function (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Second, in their meta-analysis, Langner and Eickhoff (2013) indicated that bilateral frontal activation was present during neuropsychological tasks of vigilance, thus lending more evidence to vigilance being an executive functioning task. Based on these findings, we included vigilance as an executive domain in the current meta-analysis. Accordingly, the five executive domains we included were vigilance, inhibition, working memory, shifting, and generativity.

Given the high prevalence of SDB in children and adolescents and mixed findings regarding the associations between SDB and deficits in cognitive function, we sought to better characterize the degree of executive dysfunction in children and adolescents related to SDB using meta-analysis. Meta-analysis provides systematic methods for data extraction and synthesis that can quantify the effect and confidence interval (CI) of a particular treatment or condition across studies and enable replication (Borenstein, Hedges, Higgins, & Rothstein, 2009).

Our purposes in conducting this meta-analysis is to understand the magnitude and its precision of the effect of SDB on executive function in children by comparing children with SDB to healthy controls on measures of executive function based on primary cross-sectional studies. We also evaluate executive function within SDB by severity of SDB. We also include both objective and questionnaire measures of executive function and analyze five different domains of executive function to determine their association with pediatric SDB.

METHODS

We used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to clearly state our methods and ensure reproducibility (Moher, Liberati, Tetzlaff, Altman, & PRISMA Group, 2009).

Identification and Selection of Source Studies

We searched the electronic databases and hand searched the reference section of identified articles in the following order: (1) PsychInfo, (2) PubMed, (3) hand search, and (4) Web of Science. We searched for articles related to 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)".

Inclusion Criteria

We considered for inclusion peer reviewed articles published up through December 2015. We did not set a lower limit on

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the date of publication, but all articles that met criteria were published between the years 2000 and 2014. We included studies that assessed executive function in school-age children or adolescents (age 5 to 17 years) diagnosed with SDB or sleep apnea *via* polysomnography that included either validated neuropsychological measures or validated questionnaire data compared to a healthy, age-matched control group. The studies had to be published in a peer-reviewed journal and be written in English. All studies had to contain (1) means and standard deviations (or standard errors), (2) correlation coefficients, (3) *t* or *Z* values, or (4) *F* ratios to compare executive function between groups. While we considered studies that did not report means and standard deviations but that included information from which an effect size could be calculated (e.g., *t* or *Z* values, *F* ratios), all of the studies that met inclusion criteria provided means and standard deviations or standard errors. Thus, we did not use *t* or *Z* values or *F* ratios to calculate effect sizes from any of the source studies.

Data Extraction

From studies meeting inclusion criteria, two trained members of the research group independently extracted the name of the first author, year of publication, sample size, means, and standard deviations (or standard error) from the scores on the tests of executive function used in each study. They also extracted mean age, and when available the percent of female subjects, body-mass index *Z* scores (BMI-z), measures of apnea, and oxygen nadir levels for mild, moderate, and severe levels of SDB and the healthy control groups. The extractors discussed any differences in the extracted data to resolve discrepancies. We extracted all of the results from the tests of executive function in each study and in each severity group, even if more than one test of executive function was reported.

Group Categorization by SDB Severity

We classified severity based on the mean apnea-hypopnea (AHI) index where available. The categorization for each study can be found in Table 1. If mean AHI was not available, then we used AHI ranges. Finally, if neither mean AHI nor AHI range was available, then we used a respiratory disturbance index (RDI) range. Consistent with previous research, we classified as mild children with an AHI or RDI less than 1 but who had persistent snoring. The moderate group consisted of children with an AHI or RDI score between 1 and 5; the severe group had an AHI or RDI greater than 5 (Amin et al., 2002; Owens, Spirito, Marcotte, McGuinn, & Berkelhammer, 2000).

Statistical Analysis and Data Synthesis

We used Comprehensive Meta-Analysis version 2.0 (Biostat, Englewood, NJ) to calculate effect sizes and homogeneity statistics and address publication bias (fail-safe N; funnel plots). Rosenthal's Fail-safe N estimates the number of studies that would be required to bring the *p* value for any statistically significant effect size above 0.05. We also used funnel plots to evaluate for potential publication bias. A funnel plot shows the relation between study size or precision and effect size. We plotted effect sizes of the source studies on the x-axis and the standard errors on the y-axis. There should be a symmetrical distribution around the mean effect size if publication bias is not present. Asymmetry shown by "missing" studies with large standard errors but small effect sizes in the context of small studies with large effect sizes suggests publication bias (Borenstein et al., 2009).

To estimate effect sizes, we first calculated a summary Hedges' *g* effect size using a random-effects model from each individual source study by executive domain: vigilance, inhibition, working memory, shifting, and generativity. Table 2 shows the tests of executive function included in each domain, as well as which tests we used from each study. For example, Halbower et al. (2006) provided results for both letter fluency and category fluency, and in this case, we combined these two results into a single Hedges' *g* effect size instead of using two effects sizes to prevent the participant sample from being over represented in the in the summary effect sizes. We did not combine questionnaire data with objective neuropsychological data in any analyses but instead analyzed questionnaire data separately from objective neuropsychological measures.

Only two of the source studies included both questionnaire data and objective neuropsychological measures. Second, we combined the effect sizes from each source study into an overall Hedges' *g* summary effect size using a random-effects model for each executive domain. In this way, each study was only represented once in this overall effect size analysis to avoid over representing the results of any one study in the analysis. Figure 1 shows the forest plots for each objective executive domain. Forest plots show the mean effect size for each study used in each domain, and also provides the overall mean effect size and 95% CI for each overall executive domain.

To examine whether SDB severity was associated with executive function, we calculated a Hedges' *g* for each of the three SDB severity groups and used Q-tests to determine whether effect sizes differed by SDB severity.

RESULTS

Search Results

We reviewed the titles and abstracts of articles potentially meeting inclusion criteria based on the search terms resulting in 1717 full articles for further review of abstracts (Psych Info = 487, Pubmed = 1042, manual searches of reference lists = 133, Web of Science = 55). We retrieved full reports from 32 studies (Psych Info = 9, Pubmed = 17, manual

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Table 1. Sample size and SDB criteria (mean apnea/hypopnea index, range of apnea/hypopnea index, or range of respiratory disturbance index) in source studies

	Control group	Mild	Moderate	Severe
Article	*N* (SDB criteria)	*N* (SDB criteria)	*N* (SDB criteria)	*N* (SDB criteria)
Beebe et al., 2004	17 (AHI < 1)	17 (0.1)	9 (2.4)	6 (13.4)
Beebe et al., 2010	37 (0.4)	26 (0.5)	58 (2.7)	42 (11.6)
Biggs et al., 2011	34 (0.1)	55 (0.3)	22 (2.4)	16 (16)
Blunden et al., 2000	16 (no snoring)	16 (RDI < 1)		
Bourke et al., 2011a	35 (0.1)	54 (0.3)	22 (2.4)	18 (15.9)
Bourke et al., 2011b	35 (0.1)	57 (0.3)	24 (2.4)	18 (15.8)
Calhoun et al., 2009	413 (AHI < 1)		152 (≥1 AHI < 5)	6 (AHI ≥ 5)
Esposito et al., 2013	92 (0.4)			79 (9.9)
Giordani et al., 2008	26 (0.07)			40 (5.6)
Halbower et al., 2006	12 (0.2)			19 (34.6)
Hannon et al., 2012	20 (AHI < 1.5)		17 (AHI < 1.5)	
O'Brien et al., 2004	35 (0.4)			35 (9.8)
Quan et al., 2013	43 (RDI < 4/hour)			43 (9.5)
Tan et al., 2014	16 (0.9)		15 (4.7)	

Note. SDB = sleep-disordered breathing; AHI = apnea/hypopnea index; RDI = respiratory disturbance index.

searches of reference lists = 4, Web of Science = 2) for critical analysis. Of these, 14 studies met inclusion criteria (Psych Info = 5, Pubmed = 7, manual searches of reference lists = 1, Web of Science = 1; Table 1). The total sample from these fourteen studies consisted of 1697 children with ages ranging from 5 to 17 years with a mean age of 9.81 (SD = 0.34) years. Females made up 45.75% of the sample. The neuropsychological measures used for each domain are shown in Table 2, and BMIz data and sleep characteristics by SDB severity can be found in Table 3.

Meta-Analysis

Vigilance

Objective neuropsychological measures of vigilance had an effect size near zero of –0.021 (95% CI [–0.171, 0.130]; p = .789). The CI for vigilance is small, thus providing a tight range for the actual effect size (Table 4; Figure 1). A Q-test analysis demonstrated that there were no significant effect size differences between severity groups (Q = 2.679; p = .262) (Table 5).

Inhibition

The effect size for objective neuropsychological measures of inhibition was near zero of 0.076 (95% CI [–0.134, 0.286]; p = .479), while the effect size for parent-reported impairments in inhibition was medium (Hedges g = –0.640; 95% CI [–1.154, –0.127]; p = .015) (Table 4; Figure 1). The CI for objective measures of inhibition was relatively narrow. However, due to the wide range of the CIs for questionnaire data of inhibition, our confidence in the accuracy of the estimated effect size is lower. A Q-test analysis demonstrated that there were no significant differences in effect sizes between severity groups on either objective measures of inhibitory control (Q = 2.220; p = .330) or parent-report measure, (Q = 3.238; p = .198) (Table 5).

Working memory

Objective neuropsychological measures of working memory had an effect size near zero of –0.03 (95% CI [–0.303, 0.158]; p = .536), while questionnaire reports of working memory demonstrated a large effect size, (Hedges g = –1.064; 95% CI [–1.256, –0.872]; p < .001) (Table 4; Figure 1). The CIs for both objective and questionnaire data of working memory were moderate in width. The classic fail-safe N test showed that an additional 222 studies with non-significant results would be needed to bring the p values for the parent reported measures to above 0.05. Results from the Q-test analysis demonstrated that there were no significant differences in effect sizes between severity groups on either objective measures of working memory (Q = 1.372; p = .503) or parent-report measures (Q = 3.106; p = .212) (Table 5).

Shifting

Objective neuropsychological measures of set-shifting had a medium but statistically non-significant effect-size (Hedges g = –0.445; 95% CI [–1.086, 0.196]; p = .174) (Table 4; Figure 1). The CI is broad and as such our confidence regarding the actual effect size is limited. A Q-test analysis showed that there were no significant effect size differences between severity groups (Q = 1.347; p = .245) (Table 5). Parent report measures of set-shifting demonstrated a large effect size, (Hedges g = –0.861; 95% CI [–1.111, –0.610]; p < .001) (Table 4; Figure 1). The CIs for questionnaire date of shifting were moderately broad. Results of the Q-test analysis showed that there were no significant differences in

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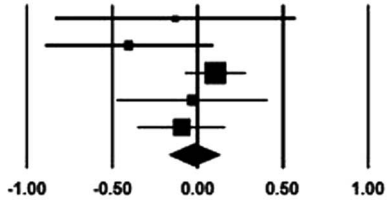
Table 2. List of the tests that were used in each domain, and their study source

Article	Vigilance	Inhibition	Working Memory	Generativity	Shifting
Beebe et al., 2004	**GDS omission errors**	**GDS commission errors, Stroop,** *BRIEF Inhibit*	*BRIEF Working Memory*	—	*BRIEF Shift*
Beebe et al., 2010	**GDS correct**	**GDS commission errors, Stroop**	**Digit Span**	**Verbal Fluency**	**WCST perseverative and non-perseverative errors**
Biggs et al., 2011	—	—	*BRIEF Working Memory,* **CogHealth Working Memory**	—	—
Blunden et al., 2000	—	—	**Digit Span**	—	—
Bourke et al., 2011a	—	*BRIEF Inhibit*	*BRIEF Working Memory*	—	*BRIEF Shift*
Bourke et al., 2011b	—	—	—	**COWAT**	—
Calhoun et al., 2009	**GDS vigilance errors**	**GDS distractibility errors, Stroop**	**Digit Span**	—	**WCST total errors**
Esposito et al., 2013	—	—	—	—	**MCST total errors, perseverative errors, and non-perseverative errors**
Giordani et al., 2008	**IVA sustained attention**	**IVA impulsivity**	**Short-term attention numbers and sequence**	—	—
Halbower et al., 2006	**CPT omissions**	**CPT commission errors**	**Sentence Span**	**Letter Fluency, Category Fluency**	—
Hannon et al., 2012	—	**Stroop**	—		—
O'Brien et al., 2004	—	—	—	**Design Fluency**	—
Quan et al., 2013	—	—	**1-back % correct**	—	—
Tan et al., 2014	—	—	**WRAML-2 Attention Composite**	—	—

Note. Objective neuropsychological measures are in bold font, and questionnaire measures are italicized.
GDS = Gordon Diagnostic System; IVA = Integrated Visual and Auditory Continuous Performance Test; CPT = Conners' Continuous Performance Test; BRIEF = Behavior Rating Inventory of Executive Function; WRAML-2 = Wide Range Assessment of Memory and Learning- Second Edition; COWAT = Controlled Oral Word Association Test; WCST = Wisconsin Card Sorting Test; MCST = Modified Card Sorting Test.

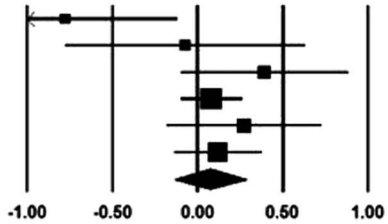
Vigilance

Study name	Point estimate	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Halbower 2006	-0.129	0.359	0.129	-0.833	0.575	-0.359	0.719
Giordani 2008	-0.403	0.251	0.063	-0.895	0.089	-1.606	0.108
Calhoun 2009	0.105	0.092	0.008	-0.075	0.285	1.141	0.254
Beebe 2004	-0.032	0.224	0.050	-0.471	0.407	-0.143	0.886
Beebe 2010	-0.093	0.131	0.017	-0.350	0.164	-0.710	0.478
	-0.021	0.077	0.006	-0.171	0.130	-0.267	0.789



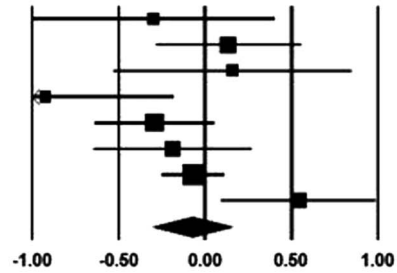
Inhibition

Study name	Point estimate	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Hannon 2012	-0.776	0.335	0.112	-1.433	-0.119	-2.316	0.021
Halbower 2006	-0.072	0.359	0.129	-0.776	0.632	-0.201	0.841
Giordani 2008	0.392	0.251	0.063	-0.100	0.884	1.562	0.118
Calhoun 2009	0.081	0.093	0.009	-0.101	0.263	0.871	0.384
Beebe 2004	0.274	0.231	0.053	-0.179	0.727	1.186	0.236
Beebe 2010	0.118	0.131	0.017	-0.139	0.375	0.901	0.368
	0.076	0.107	0.011	-0.134	0.286	0.709	0.479



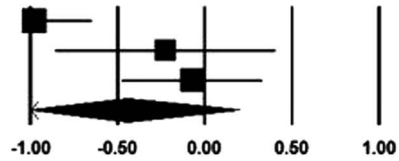
Working Memory

Study name	Point estimate	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Blunden 2000	-0.297	0.357	0.127	-0.997	0.403	-0.832	0.405
Quan 2014	0.134	0.214	0.046	-0.285	0.553	0.626	0.531
Tan 2013	0.161	0.351	0.123	-0.527	0.849	0.459	0.646
Halbower 2006	-0.924	0.378	0.143	-1.665	-0.183	-2.444	0.015
Giordani 2008	-0.292	0.177	0.031	-0.639	0.055	-1.650	0.099
Biggs 2011	-0.186	0.234	0.055	-0.645	0.273	-0.795	0.427
Calhoun 2009	-0.072	0.092	0.008	-0.252	0.108	-0.783	0.434
Beebe 2004	0.539	0.228	0.052	0.092	0.986	2.364	0.018
	-0.073	0.118	0.014	-0.303	0.158	-0.619	0.536



Shifting

Study name	Point estimate	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Esposito 2013	-0.977	0.167	0.028	-1.304	-0.650	-5.850	0.000
Calhoun 2009	-0.225	0.321	0.103	-0.854	0.404	-0.701	0.483
Beebe 2004	-0.071	0.206	0.042	-0.475	0.333	-0.345	0.730
	-0.445	0.327	0.107	-1.086	0.196	-1.361	0.174



Generativity

Study name	Point estimate	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Obrien 2004	-0.141	0.237	0.056	-0.606	0.324	-0.595	0.552
Halbower 2006	-0.593	0.320	0.102	-1.220	0.034	-1.853	0.064
Bourke 2011b	-0.220	0.145	0.021	-0.504	0.064	-1.517	0.129
Beebe 2004	-0.875	0.234	0.055	-1.334	-0.416	-3.739	0.000
	-0.427	0.173	0.030	-0.766	-0.087	-2.465	0.014

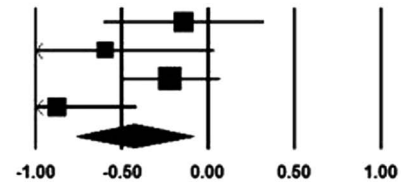


Fig. 1. Forest plots for each objective executive domain.

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Table 3. Demographic data for all study participants separated by group

Demographic	Control	Mild	Moderate	Severe
Group *N*	831	225	319	322
Age (years)	9.46 (1.71)	10.12 (1.38)	10.23 (2.28)	10.06 (2.49)
Percent female	47%	39%	47%	46%
BMIz	0.98 (0.82)	0.81 (0.63)	1.65 (1.03)	1.35 (0.79)
AHI	0.32 (0.22)	0.31 (0.09)	2.75 (0.67)	12.07 (6.46)
SpO_2	95.42 (2.22)	92.38 (0.97)	92.11 (1.28)	88.18 (6.31)

Note. Mean (*SD*), BMIz = body mass index z-score, AHI = apnea/hypopnea index, SpO_2 = oxygen nadir levels (lowest levels reached during polysomnography).

effect size between severity groups ($Q = 0.301$; $p = .860$) (Table 5).

Generativity

Objective neuropsychological measures of generativity had a medium effect size of –0.427 (95% CI [–0.766, –0.087]; $p = .014$) (Table 4; Figure 1). The CI is broad, limiting confidence about where the actual effect size is. The classic fail-safe N test showed that an additional 12 studies with non-significant results would be needed to bring the *p* values for the combined group above .05, a number that suggest that the results of this analysis are susceptible to findings from future studies. The funnel plot based on only four studies did not show clear evidence of missing studies with small effect sizes and high standard errors, although the source study with the largest effect size also had the largest standard error (Supplementary Figure 5). The *Q*-test showed there were no significant effect size differences between severity groups on measures of generativity ($Q = 1.277$; $p = .528$) (Table 5).

DISCUSSION

In this meta-analysis, we found that SDB in children and adolescents was associated with poorer performance in only some aspects of executive function compared to healthy controls. Specifically, on objective measures, children and adolescents with SDB differed from healthy controls in only one—generativity—of the five executive domains included in this analysis. There were no differences in objective assessments of vigilance, inhibition, working memory, or shifting. However, the effect size for objective neuropsychological measures of shifting had a similar, medium effect size, but was not statistically significant. In contrast, in the questionnaire data, children with SDB differed from controls on all three executive domains analyzed: inhibition, shifting, and working memory. Finally, we found that the effect sizes of the association between SDB and executive function did not differ between groups based on SDB severity. To our knowledge, this is the first meta-analysis examining the association between SDB and executive function in children and adolescents.

The reasons for not finding more associations between SDB severity and executive function in children and adolescents are unclear; however, this lack of association could be due to a lack of sensitivity in the included measure of executive function. Another possible reason this lack of association may be due to the limited number of studies. However, it is important to note that, although the number of studies is limited, the sample size for many of the analyses was large (Table 4), making low statistical power less likely to account for the lack of association between SDB and the various executive function domains.

Table 4. Results from the meta-analysis by executive domain, and by assessment type (objective neuropsychological measures and questionnaire measures)

					95% CI			Homogeneity statistics		
	k	*N*	Hedges' *g*	*SE*	Lower	Upper	*p*-Value	*Q*	df	*p*-Value
Objective measures by domain										
Vigilance	5	880	–0.021	0.077	–0.171	0.130	0.789	4.529	4	.339
Inhibition	6	917	0.076	0.107	–0.134	0.286	0.479	9.023	5	.108
Working memory	8	993	–0.073	0.118	–0.303	0.158	0.536	15.801	7	.027
Shifting	3	809	–0.445	0.327	–1.086	0.196	0.174	12.959	2	.002
Generativity	4	284	–0.427	0.173	–0.766	–0.087	0.014	7.147	3	.067
Questionnaire data by domain										
Inhibition parent-report	2	178	–0.640	0.262	–1.154	–0.127	0.015	3.538	1	.060
Working memory parent-report	3	305	–1.064	0.098	–1.256	–0.872	0.000	0.285	2	.867
Shifting parent-report	2	178	–0.861	0.128	–1.111	–0.610	0.000	0.003	1	.953

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Table 5. Results from the meta-analysis by executive domain, sleep-disordered breathing severity, and by assessment type (objective neuropsychological measures and questionnaire measures)

					95% CI			
	k	*N*	Hedges *g*	*SE*	Lower	Upper	Overall *Q*	*p-Value*
Objective measures by domain								
Vigilance							2.679	.262
Mild	2	97	−0.121	0.202	−0.517	0.275		
Moderate	3	686	0.077	0.085	−0.088	0.243		
Severe	5	618	−0.167	0.136	−0.433	0.099		
Inhibition							2.220	.330
Mild	2	97	0.309	0.181	−0.045	0.663		
Moderate	4	723	−0.063	0.192	−0.438	0.313		
Severe	5	618	0.033	0.163	−0.287	0.353		
Working memory							1.372	.503
Mild	3	155	0.140	0.175	−0.203	0.484		
Moderate	4	678	−0.075	0.156	−0.381	0.231		
Severe	6	675	−0.141	0.188	−0.510	0.229		
Shifting[a]							1.347	.245
Moderate	2	591	0.011	0.092	−0.169	0.191		
Severe	3	613	−0.479	0.412	−1.286	0.329		
Generativity							1.277	.528
Mild	2	123	−0.509	0.262	−1.023	0.006		
Moderate	2	83	−0.619	0.368	−1.341	0.103		
Severe	4	177	−0.253	0.158	−0.562	0.057		
Questionnaire data by domain								
Inhibition questionnaire							2.238	.198
Mild	2	123	−0.381	0.203	−0.780	0.017		
Moderate	2	83	−0.914	0.256	−1.417	−0.412		
Severe	2	76	−0.365	0.245	−0.845	0.115		
Working memory questionnaire							3.106	.212
Mild	3	212	−0.653	0.240	−1.124	−0.182		
Moderate	3	139	−1.042	0.200	−1.434	−0.651		
Severe	3	126	−0.561	0.207	−0.966	−0.156		
Shifting questionnaire							0.301	.860
Mild	2	123	−0.928	0.216	−1.352	−0.504		
Moderate	2	83	−0.763	0.209	−1.172	−0.354		
Severe	2	76	−0.841	0.228	−1.287	−0.394		

[a]Only one study provided objective neuropsychological data for the set-shifting domain in the mild group, and consequently objective neuropsychological data for the set-shifting domain in the mild group was not included in the table.

In the analyses looking at effect sizes according to SDB severity, sample sizes were small in some of the domains of executive function, raising the possibility of low statistical power as a reason for failing to find an association (Table 5). In adults, however, SDB severity has been associated with worse executive function, with greater severity associated with larger effect sizes (Olaithe & Bucks, 2013). The lack of an association between SDB severity and executive function we found could also indicate that executive dysfunction is independent of SDB severity in children (Bourke et al., 2011b).

A lack of association between cognitive function and severity of the associated condition has been found in other conditions affecting cognition. For example, deficits in working memory do not appear to be associated with the severity of positive or negative symptoms in schizophrenia (Forbes, Carrick, McIntosh, & Lawrie, 2009). Another possibility for the lack of dose response between SDB severity and executive dysfunction in children and adolescents could be related to length of time with SDB. SDB and OSA may not affect cognition immediately; instead, chronic hypoxic injury over time may be the reason for cognitive dysfunction (Beebe & Gozal, 2002).

As such, the larger effect sizes seen in adult studies (Olaithe & Bucks, 2013) may be related to the comparatively greater amount of time that some adults may have had with SDB compared to the length of time that children have had SDB. However, all of the studies included in the meta-analysis of adults with SDB conducted by Olaithe and Bucks (2013) had an average AHI of greater than 5 and the overall average AHI across all included studies was 47.58, a value considered to be in the severe range. Finally, executive

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function in children and adolescents may be more resilient to SDB compared to adults for reasons that our study was not designed to identify.

The effect sizes from the objective neuropsychological measures of the executive function domains referred to as vigilance, inhibition, and working memory were near zero. However, the 95% CIs for these domains ranged from small to medium, and consequently, these effect size estimates appear to be quite accurate. Generativity, which had a medium effect size (Hedges' $g = -0.427$; 95% CI [–0.766, –0.087]), was the only domain measured with objective tests that was statistically significant, although the 95% CI was broad, weakening our ability to know how large the actual effect size is. The executive domain of shifting had a slightly larger effect size than generativity (Hedges' $g = -0.445$; 95% CI [–1.086, 0.196]), but was not statistically significant.

Similarly, the 95% CI for shifting was broad, making our precision of the estimated effect size less precise. In contrast to the objective assessments of executive function, the three executive domains measured with questionnaires—inhibition, working memory, and shifting—were all statistically significant. Inhibition had a medium effect size, while both working memory and shifting had a large effect sizes. These findings may have important implications for clinical neuropsychological assessment of children with SDB. Objective neuropsychological measures of attention and executive function and informant report of these cognitive abilities may play separate but important roles in the assessment of SDB-related neuropsychological function, similar to the assessment of ADHD (Barkley & Murphy, 2010).

We found substantial differences between objective neuropsychological measures and parent- and teacher-report questionnaire data regarding executive functions associated with SDB. Effect sizes obtained from questionnaire data were substantially larger than those of neuropsychological test measures. This is consistent with findings from studies in pediatric samples of other neuropsychological disorders (Gross, Deling, Wozniak, & Boys, 2015; Vriezen & Pigott, 2002), as well as in prior studies of pediatric SDB (Biggs et al., 2011; Marcus et al., 2013).

One possible reason for the differences in effect sizes obtained from objective neuropsychological testing compared to those obtained from questionnaires may be related to the ecological validity and sensitivity of these methods when identifying executive deficits in SDB. That is, questionnaire data may represent performance during daily activities that are not necessarily captured when using lab-based objective neuropsychological measures (Marcus et al., 2013). Some have described the difference between objective measures and ratings/questionnaire data, as the former measuring "processing efficiency" and the latter as "individual goal pursuit" (Toplak, West, & Stanovich, 2013).

Questionnaire assessment of executive functioning is thought to be ecologically valid, although commonly used questionnaires of executive functioning (e.g., BRIEF) have also been criticized for being overly sensitive. However, some argue that questionnaires of executive functioning are not overly sensitive but may be better able to properly detect executive dysfunction (Roth, Erdodi, McCulloch, & Isquith, 2015). Along these lines, Barkley and Fischer (2011) found that in adults diagnosed with ADHD in childhood who had been followed over time and re-evaluated in their mid-twenties, questionnaire data was better at predicting difficulties in major life activities (e.g., job performance as reported by supervisors) than were objective measures.

Similarly, findings regarding the extent to which objective neuropsychological measures of executive function have ecological validity appear to be mixed (Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Toplak, Bucciarelli, Jain, & Tannock, 2009; Vriezen & Pigott, 2002). Alternatively, a possible reason for the discrepancy between objective and questionnaire data could be that parent expectations may bias their ratings of the severity of executive dysfunction in their children (Beebe, 2006; Biggs et al., 2011). Therefore, there are both advantages and disadvantages to using questionnaire data regarding executive functioning in the cognitive assessment of executive function in children with SDB.

It is unclear whether executive function associated with SDB found in children and adolescents changes following with treatment. In this regard, Ferini-Strambi et al. (2003) found that before treatment, adults with OSA have dysfunction in several cognitive domains, including attention, visuospatial learning, executive function, motor performance, and constructional abilities. Following treatment with continuous positive airway pressure, the subjects improved in all domains except executive functioning and constructional abilities. However, in a meta-analysis conducted on adults with OSA treated with continuous positive airway pressure, Kylstra, Aaronson, Hofman, and Schmand (2013) found that only attention improved with treatment and that the effect size was small ($d = .19$).

In contrast, children treated for SDB *via* adenotonsillectomy showed substantial improvement on measures of executive functioning at one year post-treatment (Chervin et al., 2006), suggesting that at least under some circumstances improvement in executive dysfunction associated with SDB in children may occur with treatment, possibly due to the increased neuroplasticity of the developing brain in response to injury (Johnston, 2009). However, a large randomized trial of adenotonsillectomy did not find significant change in executive function at seven months follow-up on objective measures, although there were improvements on the BRIEF per parent report and there were improvements in polysomnographic measures (Marcus et al., 2013).

This meta-analysis has several limitations. First, the included age range was broad. We included children and adolescents ages 5 to17 years, a range that spans a large spectrum of development. It is possible that effect sizes could differ across different stages of development. Second, was the limited number of studies meeting inclusion criteria. Only 14 studies containing a total of 1,697 subjects met inclusion criteria, leaving the results of this meta-analysis susceptible to findings from additional studies. As in all meta-analyses, publication bias, that is, the possibility of non-significant

findings particularly from studies containing a small number of subjects not being published, may affect the results. However, we addressed this issue by reporting results from the classic fail-safe N test. Third, was the heterogeneity in SDB severity definitions between studies. The studies used in the analyses did not all use identical apnea-hypopnea index (AHI) cutoffs to describe severity groups, possibly obscuring boundaries between the severity groups. To attempt to account for this, we grouped studies on polysomnographic variables rather than by the group severity descriptors of mild, moderate and severe used in the various source studies.

Thus, the average AHI and SpO_2 values suggested adequate groupings of SDB severity as indicated by the expected differences between groups in these polysomnography measures (Amin et al., 2002; Beebe et al., 2004; Owens et al., 2000). Because we used group averages, it is possible that some individual participants may have been included in the incorrect group. Finally, as in all meta-analyses, the significance of findings is contingent upon the methodologies used in the source studies. Some of the potential limitations, as outlined in a comprehensive review of SDB in children (Beebe, 2006), may include things such as recruitment bias in that children recruited through a sleep clinic may be different in significant ways from those with similar conditions that are not referred for a clinical exam, control groups that are above average, and whether or not the examiners were blinded to diagnosis. We acknowledge these potential limitations in our study.

CONCLUSION

Regardless of SDB severity and in the context of the study's limitations, the results of this meta-analysis indicate that SDB in children and adolescents is associated with lower performance compared to controls in only one of five executive functioning domains assessed with objective measures of executive function. Furthermore, the size of this effect was only slightly less than half of a standard deviation which would probably not be considered an impairment.

In contrast to objective measures, questionnaires of executive functioning appear to suggest impairment in multiple executive function domains in pediatric SDB. Additional studies will be needed to investigate differences between objective neuropsychological measures and questionnaire data and may be helpful in identifying moderators that increase or decrease executive dysfunction in children with SDB.

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Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S1355617716000643

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