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Executive function performance in obesity and overweight individuals: A meta-analysis and review

Yingkai Yang[a,*], Grant S. Shields[b], Cheng Guo[a,*], Yanling Liu[a]

[a] The Lab of Mental Health and Social Adaptation, Faculty of Psychology, Research Center of Mental Health Education, Southwest University, Chongqing, China
[b] Department of Psychology, University of California, Davis, CA, USA

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ABSTRACT

Prior research has suggested that obesity/overweight may be associated with deficits in executive function. If true, this has important clinical implications. In this review, we synthesize the current literature by conducting a meta-analysis of studies comparing executive functions in overweight/obese individuals to normal weight controls. We identified 72 studies—with 4904 overweight/obese participants—that met our inclusion criteria. Effect sizes were analyzed using the robust variance estimation random effects meta-regression technique. It was found that obese participants showed broad impairments on executive function, including on tasks primarily utilizing inhibition, cognitive flexibility, working memory, decision-making, verbal fluency, and planning; overweight participants only showed significant deficits in inhibition and working memory. The only moderator of effects of obesity to emerge significant was the task used to assess the respective executive function, which moderated effects of obesity on working memory and decision-making. There were not enough studies of overweight individuals to make strong claims about moderating effects in those studies. In sum, current evidence supports the existence of broad executive function deficits in obese individuals, and inhibition and working memory deficits in overweight individuals.

1. Introduction

The prevalence of obesity and overweight is rising problematically in developed and developing nations worldwide (Ng et al., 2014). The World Health Organization reported that in 2014, more than 600 million adults were obese and over 1.9 billion were overweight (World Health Organization, 2017). This fact has far-reaching and costly implications, because excessive weight contributes to the development of numerous diseases, including cardiovascular disease (Lavie et al., 2009), diabetes (Mokdad et al., 2003), and some cancers (Kyrgiou et al., 2017), and it is a risk factor for psychiatric disorders such as depression and anxiety (Luppino et al., 2010). Not surprisingly, excess weight has become a cause of growing health care costs (Withrow and Alter, 2011) and accounts for over 2.8 million deaths per year (World Health Organization, 2017).

While it is clear that obesity/overweight correlate with poor mental and physical health, recent studies have linked overweight and obesity to poorer cognitive functioning. In particular, research has suggested that individual cognitive performance declines with increases in body mass index (BMI) (Bocarsly et al., 2015; Smith et al., 2011; Vainik et al., 2013). These deficits can be observed throughout life, from childhood to late adulthood (Liang et al., 2014; Smith et al., 2011). More recently, it has been proposed that the cognitive processes collectively known as executive function may be particularly vulnerable to weight-related impairments (Appelhans, 2009; Bartholdy et al., 2016; Jansen et al., 2015; Fitzpatrick et al., 2013; Nederkoorn et al., 2006a).

1.1. Executive function

Although executive function has been defined in different ways, these definitions all share the idea that executive functions are the higher cognitive processes that enable forethought and goal-directed action (Banich, 2009; Diamond, 2013). According to an influential model of executive function (Miyake et al., 2000; Miyake and Friedman, 2012), there are three key aspects of EF: (1) inhibition, which refers to the ability to suppress impulsive or automatic (prepotent) responses, (2) cognitive flexibility, which refers to the ability to shift attention as well as mental sets or rules when situationally appropriate, and (3) working memory, which refers to the ability to monitor the relevance of incoming stimuli and update information in memory as required.

Although inhibition, cognitive flexibility, and working memory are

* Corresponding authors at: Faculty of Psychology, Southwest University, No.2 Tiansheng Street, Beibei District, 400715, Chongqing, China.
E-mail addresses: yangyk@swu.edu.cn (Y. Yang), guochen@swu.edu.cn (C. Guo).

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important aspects of EF, they may not be the only components (Snyder, 2013). Indeed, several other EF domains have been well defined in the literature (Collins and Koechlin, 2012; Lezak, 2012; Suchy, 2009; Testa et al., 2012), including (a) decision making (e.g., Rangel et al., 2008), defined as the cognitive process that occurs whenever an individual has to make a choice from several alternative possibilities, (b) verbal fluency (e.g., Troyer et al., 1997), defined as the ability to generate as many words as possible from a semantic category (or that start with certain letters) in a given time, and (c) planning (e.g., Lezak, 2012), defined as formulating, evaluating and selecting a sequence of thoughts and actions to achieve a goal.

1.2. Theories of obesity/overweight with executive function

Theories of the association between obesity/overweight and executive function agree that excessive weight should be associated with impairments in executive function (Appelhans, 2009; Castanon et al., 2014; Guillemot-Legris and Muccioli, 2017; Miller and Spencer, 2014; Nederkoorn et al., 2006a,b; Spyridaki et al., 2016; Stoeckel et al., 2017), although the exact reason for this association is still unclear.

Excessive weight may exert detrimental effects on cognition, including executive function. What's more, it is gradually becoming clearer that these deleterious effects of adiposity on cognition are not solely mediated by the commonly accepted clinical consequences (e.g., type 2 diabetes, hypoglycemic episodes, hyperlipidemia) of adiposity (Smith et al., 2011; Spyridaki et al., 2016). Recent research suggests that body mass and executive function deficits can be indirectly associated via obesity-induced activation of innate immunity which directly caused low-grade inflammation in obesity (Bourassa and Sbarra, 2017; O'Brien et al., 2017; Lasselin et al., 2016). This association is furthered by a newly proposed model, the immunologic model of self-regulatory failure, which suggested that immune system activity—especially components of the immune system involved in inflammation—impair executive function (Shields et al., 2017).

As fundamental and important aspects for lifestyle habits, it is also possible that differences on executive function could predispose individuals to excessive weight. The dual process model argues that much of our behavior is determined by an interaction between the impulsive system and the executive control system (Hofmann et al., 2009; Hofmann et al., 2012; Strack and Deutsch, 2004). In the case of excessive weight, coupled with a strong automatic approach response to high-calorie food and food cues, people who show low levels of executive control are particularly susceptible to obesity-related behaviors and outcomes (e.g., increased intake of fatty foods, weight gain), whereas those with effective cognitive control may be protected (Appelhans, 2009).

More recently, using non-invasive brain stimulation procedures, studies have found that the dorsolateral prefrontal cortex (dlPFC)—a major neural area implicated in executive function (Nee et al., 2007)—plays a casual role in the inhibition of high-calorie food craving and consumption (Hall and Vincent, 2017). For instance, in a study examining the effects of multi-session of transcranial direct current stimulation (tDCS) targeting the right dlPFC in 30 normal and overweight young adults, significant food craving reductions in the active stimulation condition (but not sham) were observed over the 5-day treatment interval and the 30-day follow up assessment (Ljubisavljevic et al., 2016). These data further suggested that executive function—or at least neural regions supporting it—may play a causal role in the development of abnormal eating behavior that increases excessive weight risk (Hall, 2016).

1.3. Evidence for impaired executive function in obesity/overweight

Despite theories converged in positing that obesity/overweight should be associated with greater impairments in executive functioning, results have been inconsistent in studies examining these associations. Many studies have indeed found significant deficits in executive function when comparing obese individuals to normal weight participants (e.g., Nederkoorn et al., 2006a,b; Kamijo et al., 2014); however, other studies have reported no significant differences in executive function between those groups (e.g., Ariza et al., 2012; Delgado-Rico et al., 2013). Researchers have consequently reached a wide range of conclusions about the relationship between excess weight and executive function, ranging from pronounced and broad impairments on neuropsychological measures of executive functioning (e.g., Cohen et al., 2011) to no apparent impairments on some aspects of executive function (e.g., Lawyer et al., 2015). In sum, although weight-related impairments in inhibition, cognitive flexibility, working memory, decision-making, verbal fluency, planning are often reported, a systematic meta-analysis is needed to assess the consistency and magnitude of such deficits.

A number of informative narrative and systematic reviews have already been conducted to summarize empirical findings regarding the effects of obesity/overweight on executive function performance. However, these reviews either (a) did not apply meta-analytical techniques to quantitatively synthesize the data (e.g., Fitzpatrick et al., 2013; Prickett et al., 2015; Stojek and MacKillop, 2017; Smith et al., 2011; Vainik et al., 2013), (b) solely focused on one outcome measure (e.g., the stop signal task) or type (e.g., cognitive flexibility) of executive function (e.g., Amlung et al., 2016; Bartholdy et al., 2016; Lavagnino et al., 2016a; McClelland et al., 2016; Rotge et al., 2017; Wu et al., 2014, 2016a), (c) only considered studies with children and adolescents (e.g., Liang et al., 2014), and/or (d) only focused on weight disorder without distinguishing between obesity and overweight (e.g., Wu et al., 2014). In addition, the number of neuropsychological studies on executive function in excess weight is growing rapidly; as such, prior meta-analytic results likely need updated to reflect the current literature, especially given increased power to detect moderating effects.

1.4. The present meta-analysis

In the current study, we conducted a quantitative meta-analysis of existing studies examining executive functions in obesity/overweight individuals as compared with normal weight comparison groups. Such an analysis is important since it allowed for a combination of effect sizes across studies and provided a more powerful estimate of true population differences.

The mixed results across studies may be due to the diversity of participant or task-related characteristics—that is, potential moderators. Therefore, a secondary aim of this meta-analysis was to identify moderators (whenever possible) of differences in executive functions between obese/overweight people and normal weight controls. The moderators we examined include age, percent of participants in the sample that were female, BMI (in adult samples), and measures of executive functions.

We considered the aforementioned factors as potential moderators mainly because previous evidence suggested that effect sizes diverged when those study characteristics differed. More specifically, previous meta-analysis on altered decision-making with excess weight revealed nonsignificant effects of excess weight in adolescent samples (Wu et al., 2016a). In addition, some researchers have obtained nonsignificant effect sizes when using some measures (e.g., stop signal task) of executive functions (e.g., Lawyer et al., 2015; Schiff et al., 2016) or examining groups that only included males (e.g., Weller et al., 2008). Finally, there is also some evidence that executive function impairments are larger in obese individuals with higher BMIs (e.g., Perpiñá et al., 2016; Fagundo et al., 2016). Therefore, given the above, we examined age, percentage of female participants, BMI, and measures of executive function as potential moderators of the differences in executive functions between obese/overweight people and normal weight controls.

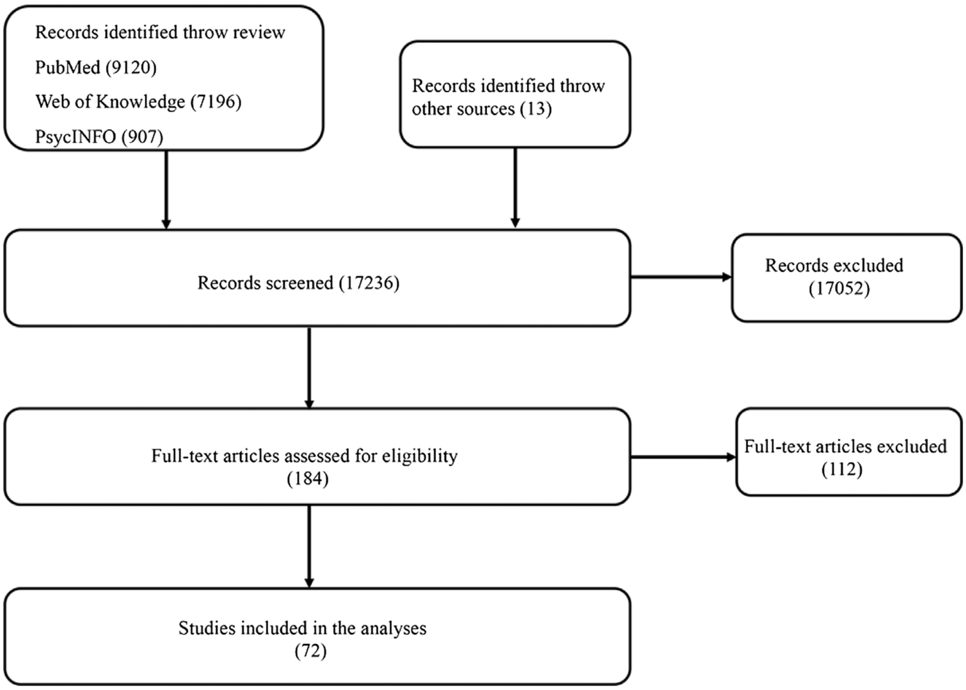

Fig. 1. Flow diagram illustrating the process of our review, screening, and article selections.

2. Method

2.1. Study selection and inclusion criteria

2.1.1. Literature review

To obtain studies for use in the meta-analysis, a topic search in the databases PubMed, ISI Web of Knowledge, and PsycINFO was conducted for all papers published until February 20, 2017 (see Supplementary material for a list of keywords). In this search; PubMed returned 9120 results; ISI Web of Knowledge returned 7196 results; and PsycINFO returned 907 results. Abstracts of articles were reviewed and the full text of an article was read whenever a paper's title or abstract indicated that the study might be relevant to analyses. In addition; to help ensure that all studies on this topic were included; references from relevant articles were reviewed; and studies that were potentially relevant were examined from those references. Finally; ProQuest Dissertations and Theses was also searched to identify unpublished dissertations. Additionally; a Google search was conducted to further identify unpublished studies. Fig. 1 outlines the detailed study selection procedure.

2.1.2. Inclusion criteria

Studies were incorporated into this meta-analysis if they (1) examined human participants (2) compared at least one group of obese or overweight individuals (minimum age 6 years) to a normal weight control group; (3) used at least one task known or shown to depend upon or assess executive function; and (4) provided data or statistical information that allowed for effect size calculation. In samples of adult participants, an obese group was defined as an average BMI of 30 kg/m^2 or above, and an overweight group as an average BMI between 25 and 30 kg/m^2. In samples of children/adolescents, obesity was defined as a BMI percentile of 95th or above, and overweight as a BMI between the 85th and 95th percentile; if BMI percentile was not reported, international cutoff points of BMI were used for defining obesity and overweight (Cole et al., 2000). In addition, we excluded studies which explicitly indicated that all their overweight/obese participants had a known severe mental illness (e.g., depression, schizophrenia, binge eating disorder).

2.1.3. Selected studies

Our search and study inclusion criteria led to the incorporation of 72 studies, 71 of which were published in peer-reviewed papers, and 1 of which was an unpublished thesis. Of these 72 studies, 44 assessed differences between obese/overweight individuals and normal weight on inhibition, 25 assessed differences in cognitive flexibility, 22 assessed differences in working memory, 29 assessed differences in decision-making, 9 assessed differences in verbal fluency, and 8 assessed differences in planning.

2.2. Coding of variables

Executive function tasks were coded as assessing inhibition, cognitive flexibility, working memory, decision-making, verbal fluency, or planning based upon previous empirical or theoretical evidence suggesting that a given task primarily utilized the particular coded executive function. See the Supplementary material Table S1 for a complete description of task coding. This list is not meant to be exhaustive of all executive functions, but rather of the range of neuropsychological measures of executive function included in the obesity/overweight literature.

Within the obese or overweight groups, mean age, percentage female participants, and BMI were coded as continuous variables. Measures of executive function were contrast coded and submitted to F tests (as described below) to examine differences.

The methodological quality of included studies was assessed through a linear combination of factors that may influence obtained differences in executive function between obese/overweight individuals and normal weight individuals such that a higher score indicated better precision in assessing potential executive function differences. Where exclusion of age, gender, IQ/socioeconomic status (SES) and education differences, illnesses, medication use, are all dummy-coded as 1 for excluded and 0 for not excluded, the equation is as follows: Study quality = (Age Difference Excluded [0–1]) + (Gender Difference Excluded [0–1]) + (Education Difference Excluded [0–1]) + (IQ/SES Difference Excluded [0–1]) + (Illnesses Excluded [0–1]) + (Medication Excluded [0–1]) (Differences between the groups were analyzed using t-test or χ^2 tests, $p > 0.05$ means difference excluded).

Table 1
Studies included in the meta-analysis.

Study	Subject (sample size)	Female (%)	Mean age (years)	Mean BMI (kg/m^2)	Executive functions studied	Task(s) Used	Quality score (x/6)
Alarcón et al. (2016)	OB (18) OW (46) NW (88)	33.3% 45.7% 45.5%	14.4 13.8 14.2	30.9 24.2 20.3	Working memory	Spatial 2-back Verbal 2-back	5
Ariza et al. (2012)	OB (42) NW (42)	66.7% 69.1%	31.8 29.7	38.3 22.1	Inhibition Cognitive flexibility Working memory Verbal fluency	Stroop Trail Making Test B/B-A WCST Letter-Number Sequencing Phonemic Verbal Fluency	3
Benito-León et al. (2013)	OB (592) OW (850) NW (507)	62.8% 51.2% 58.4%	74.9 75.7 76.9	≥30 25–29.9 < 25	Verbal fluency	Semantic Verbal Fluency	1
Blanco-Gómez et al. (2015)	OB (130) NW (90)	46.2% 40%	8.5 8.5	N.R. N.R.	Inhibition Cognitive flexibility	Five Digit Test	4
Bongers et al. (2015)	OB (185) NW (134)	70.8% 73.9%	35.2 33.0	38.2 22.4	Inhibition Decision making	Stop Signal Task. Delay Discounting Task	3
Brogan et al. (2010)	OB (18) NW (20)	100% 100%	52.1 27.8	36.2 27.8	Decision making	The Iowa Gambling Task	3
Brogan et al. (2011)	OB (42) NW (50)	71.4% 66.0%	52.2 47.3	41.5 24.4	Decision making	The Iowa Gambling Task	3
Brooks et al. (2013)	OB (112) NW (180)	100% 100%	72.5 72.5	≥30 < 25	Cognitive flexibility	Trail Making Test B-A	2
Calvo et al. (2014)	OB (30) NW (32)	60% 53.1%	21.2 21.1	36.4 21.7	Inhibition Working memory	Go/No-Go RMCPT	5
Chamberlain et al. (2015)	OB (55) OW (110) NW (346)	60% 29.1% 34.1%	24.2 23 21.3	35.6 26.9 21.6	Inhibition Cognitive flexibility Decision making Planning	Stop Signal Task. IDEDT Cambridge Gamble Task OTSCT	1
Cohen et al. (2011)	OB (42) NW (107)	47.7% 52.3%	58.9 61.2	31.8 24.1	Inhibition Cognitive flexibility Working memory	Stroop Trail Making Test B-A WCST Digit Span Visual Memory Span Task	3
Coppin et al. (2014)	OB (17) OW (16) NW (16)	52.9% 43.8% 56.3%	25.2 24.9 24.3	36 27.6 22.4	Working memory	CCPT	5
Cserjési et al. (2007)	OB (12) NW (12)	0% 0%	12.1 12.4	27.2 16.9	Cognitive flexibility	WCST	4
Danner et al. (2012)	OB (18) NW (30)	100% 100%	44.7 36.1	30.8 22.3	Decision making	The Iowa Gambling Task	2
Delgado-Rico et al. (2012)	OB (42) NW (21)	66.7% 47.6%	14.2 14.1	29.2 19.8	Inhibition Cognitive flexibility	Stroop	5
Delgado-Rico et al. (2013)	OB (14) OW (13) NW (13)	64.3% 69.2% 61.5%	14.2 14.1 13.7	31.1 24.7 20.4	Decision making	Risk Gain Task	4
Deux et al. (2017)	OB (20 & 23) NW (59 & 57)	55%& 64.4% 56.5% &64.9%	14.4 15.3	N.R. N.R.	Inhibition	Go/no-go	2
Eisenstein et al. (2015)	OB (27) NW (20)	85.2% 75%	31.5 28.6	39.9 22.4	Decision making	Delay Discounting Task Probability Discounting Task	4
Fagundo et al. (2012)	OB (52) NW (137)	100% 100%	40.5 24.8	39.8 21.5	Inhibition Decision making	Stroop The Iowa Gambling Task	3
Fagundo et al. (2016)	OB (44 & 21) NW (49)	100% 100%	42.3 & 49.2 29	46.3 & 35.5 21.61	Inhibition Cognitive flexibility Decision making	Stroop WCST The Iowa Gambling Task	3
Fields et al. (2011)	OB (16) NW (20)	68.8% 20%	17.2 17.4	35.4 21.3	Decision making	Delay Discounting Task	3
Fields et al. (2013)	OB (21) OW (20) NW (20)	52.4% 55% 60%	14.9 15.2 15	34.4 26.1 20.4	Decision making	Delay Discounting Task	3
Galioto Wiedemann et al. (2014)	OB (36) NW (36)	61.1% 50%	21.2 20.7	36.4 22	Inhibition Working memory	Go/No-Go RMCPT	4

(continued on next page)

Table 1 (*continued*)

Study	Subject (sample size)	Female (%)	Mean age (years)	Mean BMI (kg/m^2)	Executive functions studied	Task(s) Used	Quality score (x/6)
Gameiro et al. (2017)	OB (76) NW (38)	68.4% 71.1%	43.2 40.5	> 30 18–24.9	Inhibition Shifting	Stroop WCST Color Trail Test	3
Goldschmidt et al. (2017)	OB (34 & 26) NW (15)	55.9% &61.5% 60%	10.8 &10.2 10.4	N.R. N.R.	Inhibition Cognitive flexibility Working memory Decision making Planning	Flanker Task DCCTT List Sorting Task The Iowa Gambling Task Tower of London Task	4
Gonzales et al. (2010)	OB (12) OW (11) NW (9)	50% 45.5% 77.9%	48.5 52 51.8	34.3 27.4 22.4	Cognitive flexibility Working memory Verbal fluency	Trail Making Test B Digit Span Phonemic Verbal Fluency	4
Guerrieri et al. (2008)	OW (15) NW (63)	N.R. N.R.	9 9	21.8 16.3	Inhibition Decision making	Stop Signal Task Door Open Task	2
Gunstad et al. (2007)(1)	OW (140) NW (178)	46.4% 55.1%	32.4 31.4	28.4 22.1	Inhibition Cognitive flexibility Working memory Planning	Stroop Trail Making Test B Digit Span Visual Memory Span Task Maze task	5
Gunstad et al. (2007)(2)	OW (58) NW (32)	55.1% 53.1%	60.4 58.3	29.2 23.1	Inhibition Cognitive flexibility Working memory Planning	Stroop Trail Making Test B Digit Span Visual Memory Span Task Maze Task	5
Gunstad et al. (2008)	OB (45) OW (76) NW (330)	38% 47% 51%	10.8 12.6 12.6	26.2 23.1 18.5	Cognitive flexibility Working memory Verbal fluency	Trail Making Test B Digit Span Semantic Verbal Fluency	2 & 4
Hendrick et al. (2012)	OB (13) OW (8) NW (18)	100% 100% 100%	34.8 33.2 26.2	33.2 25.6 20.0	Inhibition	Stop Signal Task	2
Hong (2013)	OB (27) NW (29)	N.R. N.R.	N.R. N.R.	> 30 18–24.9	Inhibition	Stop Signal Task	2
Hsu et al. (2015)	OB (15) OW (27) NW (24)	86.7% 55.6% 87.5%	75 74 74	32.7 27.6 22.3	Inhibition Cognitive flexibility Working memory	Stroop Trail Making Test B-A Digit Span	4 & 3
Kamijo et al. (2012a)	OB (30) OW (26) NW (70)	56.7% 46.2% 48.6%	9 8.7 8.9	26.1 19.5 16.5	Inhibition	Go/No-Go	5
Kamijo et al. (2012b)	OB (37) NW (37)	51.4% 51.4%	7.9 9	25.3 16.8	Inhibition	Go/No-Go	5
Kamijo et al. (2014)	OB (37) NW (37)	54.1% 54.1%	8.9 8.8	25.2 16.7	Inhibition	Flanker task	5
Kittel et al. (2017)	OB (22) NW (22)	81.8% 81.8%	14.8 15.2	N.R. N.R.	Inhibition Cognitive flexibility Decision making	Stroop Comprehensive Trail Making Test Iowa Gambling Task	5
Kulendran et al. (2014)	OB (53) NW (50)	60.1% N.R.	14.28 13.81	33.75 23.83	Inhibition Decision making	Stop Signal Task Delay Discounting Task	4
Kulendran et al. (2016)(1)	OB (20 & 45) NW (20)	N.R. N.R.	36.2 & 44.3 22.1	39.7 & 43.4 23.8	Inhibition Decision making	Stop Signal Task Temporal discounting task	1
Kulendran et al. (2016)(2)	OB (47) NW (50)	N.R. N.R.	14.3 13.3	33.2 20.6	Inhibition Decision making	Stop Signal Task Temporal discounting task	4
Lawyer et al. (2015)	OB (56) NW (235)	65.5% 53.6%	22.6 21.5	> 30 18–24.9	Inhibition Decision making	Stop Signal Task Delay Discounting task Probability Discounting Task	2
Loeber et al. (2012)	OB (20) NW (20)	65% 65%	47.9 44.9	38.8 22.6	Inhibition Working memory	Go/No-Go Auditive verbal learning task	4
Maayan et al. (2011)	OB (54) NW (37)	63% 56.8%	17.5 17.3	39.9 21.7	Inhibition Cognitive flexibility Working memory Verbal fluency	Stroop Trail Making Test B WRALM Phonemic Verbal Fluency	5
Mallorquí-Bagué et al. (2016)	OB (113) NW (194)	77% 79%	43.4 25	N.R. N.R.	Decision making	The Iowa Gambling Task	3

(*continued on next page*)

Table 1 (*continued*)

Study	Subject (sample size)	Female (%)	Mean age (years)	Mean BMI (kg/m²)	Executive functions studied	Task(s) Used	Quality score (x/6)
Mata et al. (2015)	OB (32) NW (22)	65.6% 54.5%	15.1 15.5	29.4 21.2	Decision making	Risky-Gains task	3
Mole et al. (2015)	OB (30) NW (30)	36.7% 36.7%	44.1 43.6	32.7 24.1	Inhibition Decision making	Stop Signal Task Delay Discounting Task	5
Moreno-López et al. (2012)	OB (36) NW (16)	72.2% 56.3%	14.2 14.1	28.5 20.3	Inhibition	Stroop	5
Navas et al. (2016)	OB (20) OW (21) NW (38)	55% 52.4% 57.9%	32.2 35 33.2	33.5 27 22.2	Decision making	The Iowa Gambling Task Wheel of Fortune Task	5
Nederkoorn et al. (2006a)	OB (15) NW (31)	60% 61.3%	13.9 13.7	25.8 19.3	Inhibition Decision making	Stop Signal Task Door Open Task	3
Nederkoorn et al. (2006b)	OB (31) NW (28)	100% 100%	40.9 41.8	39 22.5	Inhibition Decision making	Stop Signal Task Delay Discounting Task	2
Nederkoorn et al. (2012)	OW (14) NW (75)	78.6% 50.7%	8.1 8.1	21.1 16.1	Inhibition	Stop Signal Task	3
Nederkoorn (2014)	OW (45) NW (73)	84.4% 87.7%	31 29.2	29.1 21.7	Inhibition	Stop Signal Task	4
Perpiñá et al. (2016)	OW (27) NW (39)	85.2% 76.9%	47.8 31.9	43.9 23.2	Cognitive flexibility Decision making	WCST The Iowa Gambling Task	1
Pignatti et al. (2006)	OB (20) NW (20)	70% 50%	43.4 46.7	42.2 22.2	Decision making	The Iowa Gambling Task	4
Qavam et al. (2015)	OW (40) NW (40)	0% 0%	16.5 16.5	N.R. N.R.	Planning	Tower of London Task	3
Restivo et al. (2017)	OB (25) NW (20)	92% 90%	43.9 43.8	44.7 22.4	Inhibition Cognitive flexibility Verbal fluency	Stroop WCST Phonemic Verbal Fluency Semantic Verbal Fluency	2
Reyes et al. (2015)	OW (69 & 93) NW (63 & 92)	N.R. & 44% N.R. & 45.6%	10.2 10.3	N.R. & 22.5 N.R. & 17.1	Inhibition	Stroop Go/No-Go	3 & 4
Ross et al. (2015)	OB (79) NW (51)	64.6% 49%	19.6 19.4	35.6 22.9	Cognitive flexibility Working memory Planning	Trail Making Test B-A Letter-Number Sequencing WMS IV-VWMIS Tower of London Task	5
Schiff et al. (2016)	OB (23) NW (23)	78.3% 78.3%	36.2 22.8	36.2 22.4	Inhibition Cognitive flexibility Working memory	Simon Task Trail Making Test B Sternberg Task	4
Sellaro and Colzato (2017)(1)	OW (17) NW (22)	64.1% 77.3%	23.4 21.2	27.7 21.9	Inhibition	Stop Signal Task	3
Sellaro and Colzato (2017)(2)	OW (19) NW (24)	57.9% 79.2%	22.9 20.5	28.7 21.7	Inhibition	Simon Task	3
Silveira et al. (2014)	OW (9) NW (28)	55.6% 57.1%	25.4 23.1	28.3 22.2	Working memory	Letter-Number Sequencing	4
Simmank et al. (2015)	OW (26) NW (26)	50% 50%	27.1 26	34.7 22.6	Decision making	Delay Discounting Task	4
Skoranski et al. (2013)	OB (24) NW (27)	N.R. N.R.	12.8 12.8	N.R. N.R.	Inhibition	Simon Task	3
Spitoni et al. (2017)	OB (24) NW (37)	79.2% 64.9%	49.8 35.7	41.1 22.5	Inhibition Cognitive flexibility	THSCT The Rule Shift Cards	1
Stingl et al. (2012)	OB (34) NW (34)	70.6% 70.6%	36.5 38.4	30.4 22	Working memory	Visual 1-back	4
Sweat et al. (2017)	OB (108) NW (54)	63% 54%	19.6 19.4	35.6 21.5	Inhibition Cognitive flexibility Working memory Verbal fluency Planning	Stroop Trail making Test B-A Letter-Number Sequencing Semantic Verbal Fluency Tower of London Task	5
Tsai et al. (2016)	OB (26) NW (26)	30.8% 30.8%	9.5 9.5	27.4 18.5	Inhibition	Serial Reaction Time Task	4

(continued on next page)

Table 1 (*continued*)

Study	Subject (sample size)	Female (%)	Mean age (years)	Mean BMI (kg/ m^2)	Executive functions studied	Task(s) Used	Quality score (x/ 6)
Verdejo-García et al. (2010)	OB (27) NW (34)	45.8% 38.2%	14.3 15.3	31.6 21	Inhibition Cognitive flexibility Working memory Decision making Planning	Five Digit test Stroop task Trail Making Test B-A Letter-Number Sequencing The Iowa Gambling Task Zoo Map	5
Voon et al. (2014)	OB (30) NW (30)	45.8% 43.6%	44.1 43.6	32.7 24.1	Inhibition	Premature Responding Task	5
Weller et al. (2008)(1)	OB (19) NW (21)	0% 0%	19.2 19.4	35.4 22.3	Decision making	Delay Discounting Task	5
Weller et al. (2008)(2)	OB (29) NW (26)	100% 100%	19.6 20	38.4 21.9	Decision making	Delay Discounting Task	5
Wu et al. (2016b)	OB (19 & 18) NW (20 & 18)	73.7% 70%	N.R. N.R.	33 22.2	Inhibition Cognitive flexibility Working memory Verbal fluency	Stroop Trail making Test B-A Digit Span Phonemic Verbal Fluency Semantic Verbal Fluency	3
Wu et al. (2017)	OB (44) OW (23) NW (92)	31.8% 26.1% 56.5%	12.4 11.8 11.9	N.R. N.R. N.R.	Working memory	Digit Span	2
Yau et al. (2014)	OB (30) NW (30)	56.7% 63.3%	17.6 17.2	35.5 21.1	Inhibition Cognitive flexibility Working memory Verbal fluency Planning	Stroop Trail making Test B WCST & WRALM Phonemic Verbal Fluency Tower of London Task	6
Yeomans et al. (2008)	OW (31) NW (116)	100% 100%	N.R. N.R.	N.R. N.R.	Decision making	Delay Discounting Task	1

Note: N.R. = not reported; OB = obesity group; OW = overweight group; NW = normal weight group; CCPT = Conditioned cue preference test; DCCTT = Dimensional Change Card Sort Task; IDEDT = Intradimensional/ Extradimensional Task; OTSCT = OneTouch Stockings of Cambridge Task; RMCPT = Running Memory Continuous Performance Task; THSCT = The Hayling Sentence Completion Test; WCST = Wisconsin Card Sorting Test; WMS IV—VWMIS = Weschler Memory Scale IV Visual Working Memory Index Score; WRALM = Wide Range Assessment of Learning and Memory.

2.3. Statistical analyses

The effect size measure of interest was the standardized mean difference between obese/overweight and normal weight groups. Hedges' *g*, rather than Cohen's *d*, was used as the effect size for analysis, given that the former is a relatively unbiased estimate of the population standardized mean difference effect size while the latter is a biased estimate. Whenever possible, we firstly calculated Cohen's *d* from the means, standard deviations, and sample sizes presented in the article. If means and standard deviations were not reported and the design was between-studies, we used *t* or one-way *F* statistics—or *p* values resulting from tests of those two statistics—to calculate the effect size. If none of these statistics were reported, that study was excluded from analysis. Then, all Cohen's *d* effect sizes were transformed into Hedges' *g* effect sizes and used for analysis (Borenstein et al., 2009).

Given the multifaceted nature of executive function, most studies often report more than one outcome (e.g., errors of commission and errors of omission on the go/no-go task). Multiple outcomes are a problem for conventional meta-analytic methods, as averaging effect sizes within studies without accounting for their correlations can alter or obscure true effect size estimates (Scammacca et al., 2014). Thus, we employed the meta-analytic technique of robust variance estimation, a random-effects meta-regression that can account for dependence between effect size estimates (Hedges et al., 2010; Tanner-Smith and Tipton, 2014). This technique robustly estimates effect size weights and standard errors for the given effects, allowing for multiple outcomes within studies (Hedges et al., 2010). We employed the robu() function of the robumeta package, version 2.0, in **R**, version 3.4.0, to conduct these analyses using the correlated weights given by Hedges et al. (2010) with our primary analyses using the small sample corrections suggested by Tipton (2015). To account for dependency, ρ was set to the recommended 0.80 (Tanner-Smith and Tipton, 2014). To conduct *F* tests on models with contrast-coded coefficients, we used the Wald_test () function in the clubSandwich package, version 0.2.2, in **R**, with the bias-reduced linearization adjustment for clustered standard errors and degrees of freedom estimated with Hotelling's T_Z^2 method.

Degrees of freedom for all primary analyses were estimated using the Satterwaite approximation, where $df = 2/cv^2$ and *cv* represents the coefficient of variation, as simulation studies have indicated that this method of estimating degrees of freedom is most analytically valid with study set sizes under 40 using the RVE meta analytic technique (Tipton, 2015).

Finally, we used the procedures described by Viechtbauer and Cheung (2010) to derive extreme outliers (identified by inspecting z-score of the standardized residuals) and influential studies (identified by inspecting Cook's distance plots). If the z-score of the standardized residuals exceeded 1.96, the study was deemed to be an outlier. And if Cook's distance plots showed the outlier exert significant influence on the results, the outlier was excluded and only results from the meta-analysis without the outlier were reported in full.

For all of the following analyses, a negative effect size means that obese or overweight group performed worse compared to the normal weight control group, whereas a positive effect size indicates that the obese or overweight group performed better than normal weight individuals. In addition, because the outcome in these analyses is the standardized mean difference between groups (the effect size), a significant moderator means that the effect size estimate depends upon levels of that variable. We only conducted meta-regression for outcomes in which there are at least 10 samples to 1 covariate (Borenstein et al., 2009)

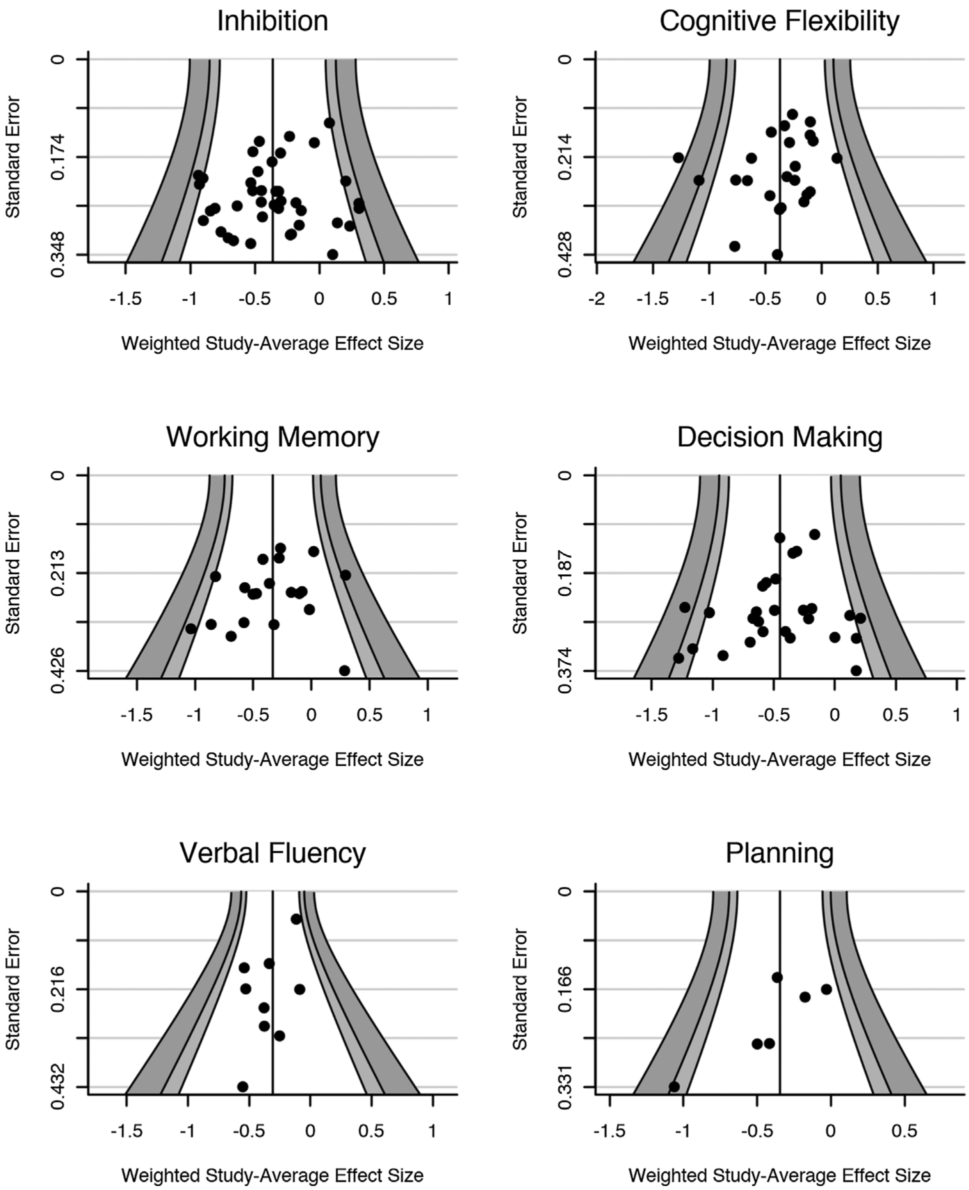

Fig. 2. Funnel plots to ascertain evidence for publication bias in obesity.

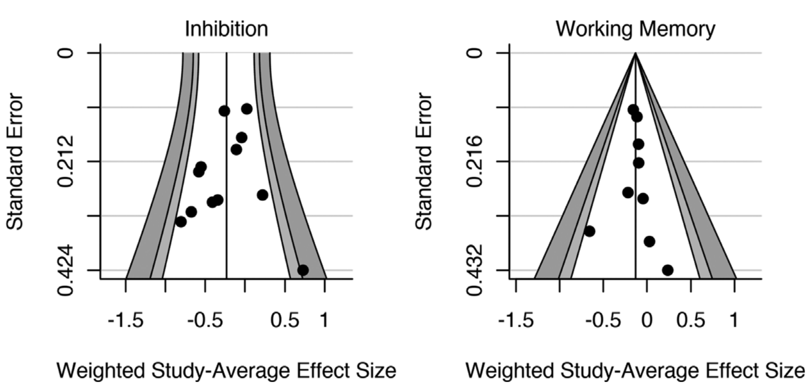

Fig. 3. Funnel plots to ascertain evidence for publication bias of inhibition and working memory in overweight.

3. Results

3.1. Preliminary analyses

3.1.1. Study characteristics

The final sample consisted of 72 studies (i.e., total $m = 72$). Of those 72 studies, 65 examined differences in executive function between obese and normal weight individuals, whereas 24 studies examined differences in executive function between overweight and normal weight individuals. There were 183 effect sizes (i.e., total $k = 183$) between obese participants and normal weight participants, and 69 effect sizes (i.e., total $k = 69$) between overweight participants and normal weight participants. The number of effect sizes per study that we obtained is relatively common in social science research (e.g.,

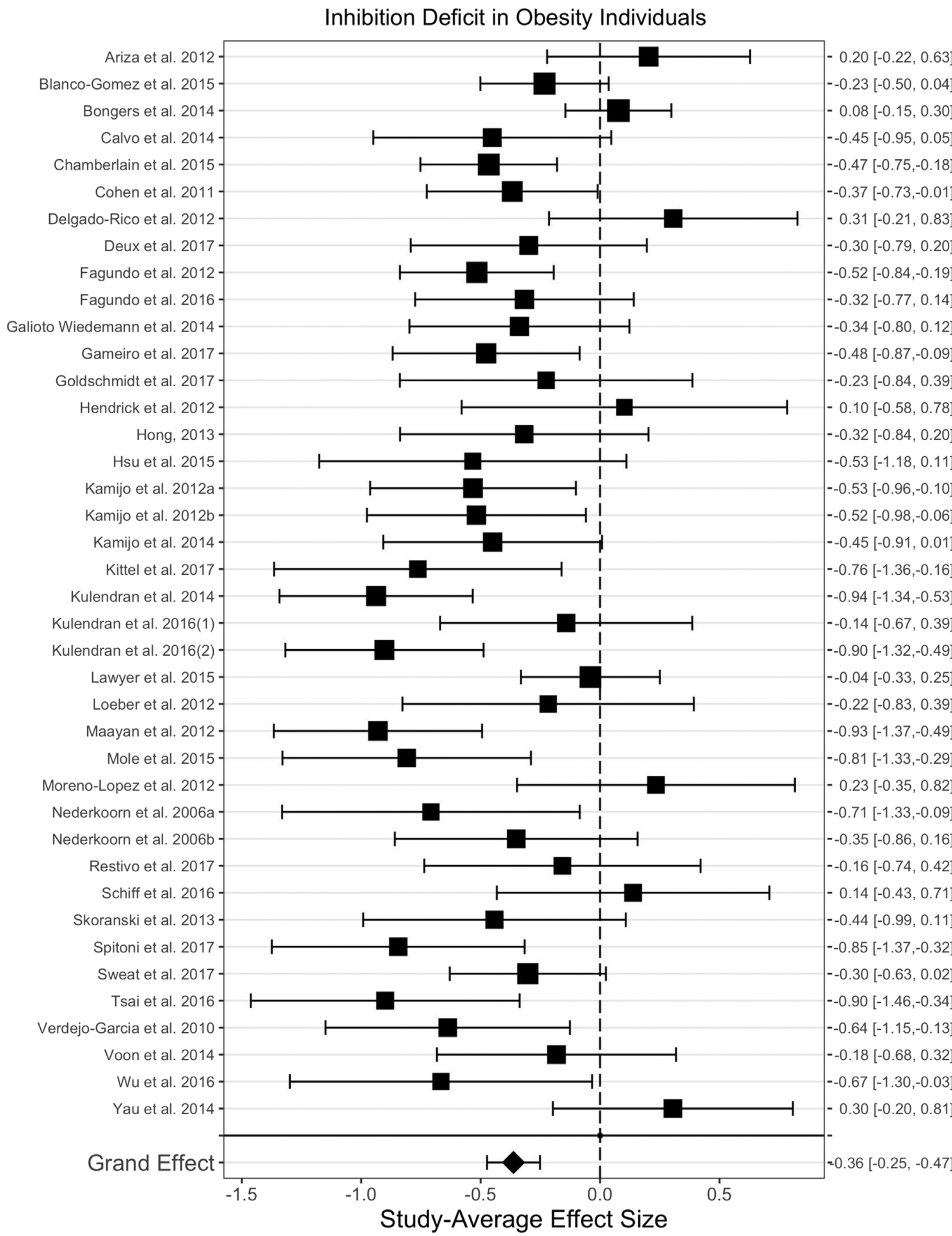

Fig. 4. Inhibition deficit in obesity individuals.

Shields et al., 2016; Yang et al., 2017).

Differences in inhibition were examined in 39 studies (k = 50) with 1782 obese participants and in 10 studies (k = 20) with 641 overweight participants. Differences in cognitive flexibility were examined in 24 studies (k = 33) with 1145 obese participants, and in 5 studies (k = 6) with 382 overweight participants. Differences in working memory were examined in 20 studies (k = 35) with 785 obese participants and in 8 studies (k = 17) with 406 overweight participants. Differences decision-making were examined in 27 studies (k = 46) with 1205 obese participants and in 6 studies (k = 18) with 210 overweight participants. Differences in verbal fluency were examined in 9 studies (k = 12) with 927 obese participants and in 3 studies (k = 4) with 897 overweight participants. Effect sizes on planning were examined in 6 studies (k = 7) with 359 obese

Table 2
Moderator analyses for studies of inhibition in obesity.

Variable	β	t	F	m	g	df	p
Participant Age	0.032	0.65				14.3	0.529
Percent Female Participants	0.064	1.31				11.4	0.217
BMI (adult sample)	0.050	0.88				8.1	0.404
Measures of inhibition			0.25			16.9	0.862
Stop Signal task				10	−0.402	9.7	0.008
Go/No-go task				6	−0.411	4.8	< 0.001
Stroop task				15	−0.311	13.5	0.008
Other				9	−0.407	7.5	0.005

Note: Significant ($p < 0.05$) moderating effects are listed in boldface font.

participants, and in 3 studies ($k = 4$) with 348 overweight participants. Table 1 presents each study and its characteristics.

3.1.2. Assessment of publication bias

Egger's test (Egger et al., 1997) for funnel plot asymmetry was used to conduct the publication bias test on each executive function individually. In assessment of obesity (Fig. 2), the test for publication bias returned nonsignificant for inhibition, $t(38) = -0.49$, $p = 0.626$; cognitive flexibility, $t(22) = -0.01$, $p = 0.995$; working memory, $t(18) = -0.33$, $p = 0.747$; decision-making, $t(27) = -0.78$, $p = 0.440$; verbal fluency $t(7) = -0.20$ $p = 0.849$; and planning, $t(4) = -0.41$, $p = 0.701$. In assessment of overweight, the test for publication bias returned nonsignificant for inhibition (Fig. 3), $t(10) = -0.50$, $p = 0.630$, cognitive flexibility, $t(4) = 0.43$, $p = 0.690$, decision making, $t(4) = -1.27$, $p = 0.274$; verbal fluency, $t(1) = 0.57$, $p = 0.671$; and planning, $t(2) = -1.63$, $p = 0.245$. The test indicated significant publication bias in studies examining working memory (Fig. 3), $t(7) = 3.40$, $p = 0.011$; notably, however, a trim and fill analysis indicated that the two missing effect sizes were associated with larger effects of overweight on working memory than the average published study. Including these estimated missing working memory studies increased the impairing effect of overweight on working memory by $B = -0.0143$. Importantly, these publication bias results did not differ if the removed, outlying effect sizes were included in analyses, indicating that removing these effect sizes did not hide any potential publication bias. Therefore, these results indicate that any effects observed in this meta-analysis are unlikely to be due to publication bias.

3.2. Primary analyses of obesity effects

3.2.1. Testing overall differences in executive functions

We first tested whether potential differences in executive functions between obese and normal weight individuals were broad and nonspecific or whether any potential differences varied by executive function domain. Results indicated that differences in executive functions between obese and normal weight individuals did not differ across the domains of inhibition, cognitive flexibility, working memory, decision-making, verbal fluency, and planning, $F(5, 16.2) = 0.51$, $p = 0.78$. However, a lack of overall differences may mask varying effects of moderators on individual executive functions. Thus, we present analyses of each executive function below.

3.2.2. Inhibition

The analysis of studies examining differences between obese and normal weight participants on measures of inhibition ($m = 39$, $k = 50$) revealed a significant overall effect, $g^+ = -0.363$, $t(37.2) = -6.62$, $p < 0.001$, 95% CI [−0.473, −0.252] (Fig. 4), such that obese participants performed worse on inhibition tasks. There was low heterogeneity across these studies' effects, $\tau^2 = 0.069$, indicating that the impaired performance on inhibition tasks was relatively consistent across various conditions. However, in the interest of examining potential factors that may contribute to some inconsistencies in studies examining effects of obesity on inhibition, we conducted moderator analyses of these effects, described below.

Moderator analyses showed that age, percentage of female participants, and BMI did not significantly moderate effects of obesity on inhibition (see Table 2). Similarly, the task used to assess inhibition did not moderate effects of obesity on inhibition, $F(3, 16.9) = 0.25$, $p = 0.862$ (see Table 2). Nine different tasks were used to assess inhibition in the studies included in our analyses of obesity effects. The most frequently used tasks were the Stroop task, the Stop Signal Task, and the Go/No-Go. The effect sizes comparing obese people to normal weight people across these tasks were comparable (see Table 2). Thus, we did not find evidence for significant moderation of effects of obesity on inhibition by age, sex, BMI, or task used to assess inhibition.

3.2.3. Cognitive flexibility

The analysis of studies examining differences between obese and normal weight participants on measures of cognitive flexibility ($m = 24$, $k = 33$) revealed a significant overall effect, $g^+ = -0.369$, $t(21) = -5.32$, $p < 0.001$, 95% CI [−0.513, −0.224] (Fig. 5), such that obese participants performed worse than normal weight participants on tasks assessing cognitive flexibility. There was low heterogeneity across these studies' effects, $\tau^2 = 0.059$, indicating that the obesity-related performance impairment on tasks requiring cognitive flexibility was relatively consistent across various conditions.

Moderator analyses showed that age, percentage of female participants, and BMI did not significantly moderate effects of obesity on cognitive flexibility (Table 3). In addition, measures of cognitive flexibility did not significantly influence the effect sizes, $F(2, 12.6) = 0.92$, $p = 0.425$ (see Table 3). Nine different tasks were used to assess overweight/obesity in the studies examining effects of obesity included in our analyses. The most frequently used tasks were the Trail Making Test (TMT), and the Wisconsin Card Sorting Test (WCST). Effect sizes comparing obese to normal weight individuals were similar across these tasks (Table 2). Thus, we did not find evidence for significant moderation of effects of obesity on cognitive flexibility by age, sex, BMI, or task used to assess cognitive flexibility.

3.2.4. Working memory

The analysis of studies examining differences between obese and normal weight participants on measures of working memory ($m = 20$, $k = 35$) revealed a significant overall effect, $g^+ = -0.333$, $t(18.0) = -4.49$, $p < 0.001$, 95% CI [−0.488, −0.177] (Fig. 6), such that obese participants performed worse than healthy weight participants on tasks utilizing working memory. There was low heterogeneity across these studies' effects, $\tau^2 = 0.071$, indicating that the obesity-related performance impairment of tasks requiring working memory was relatively consistent across various conditions.

Moderator analyses showed that age, percentage of female participants, and BMI did not significantly moderate effects of obesity on working memory (Table 4). However, the task used to assess working memory significantly moderated effects of obesity on working memory, $F(2, 6.8) = 6.98$, $p = 0.023$ (Table 4). Nine different tasks were used to assess working memory in studies comparing the working memory of obese to normal weight individuals. The most frequently used tasks were the Digit span task, and the Letter–number sequencing task. Six studies included the Digit span task, and performance on this task was significantly worse in obese than healthy weight individuals, $g^+ = -0.346$, 95% CI [−0.542, −0.149]. Four studies included the Letter–number sequencing task, but performance on this task did not differ between obese and normal weight individuals, $g^+ = 0.026$, 95% CI [−0.226, 0.279]. Other working memory tasks, used in a total of 12 studies, showed an obesity-related performance impairment similar to the digit span, $g^+ = -0.477$, 95% CI [−0.662, −0.292]. As might be clear, the moderating effect of the measure used to assess working

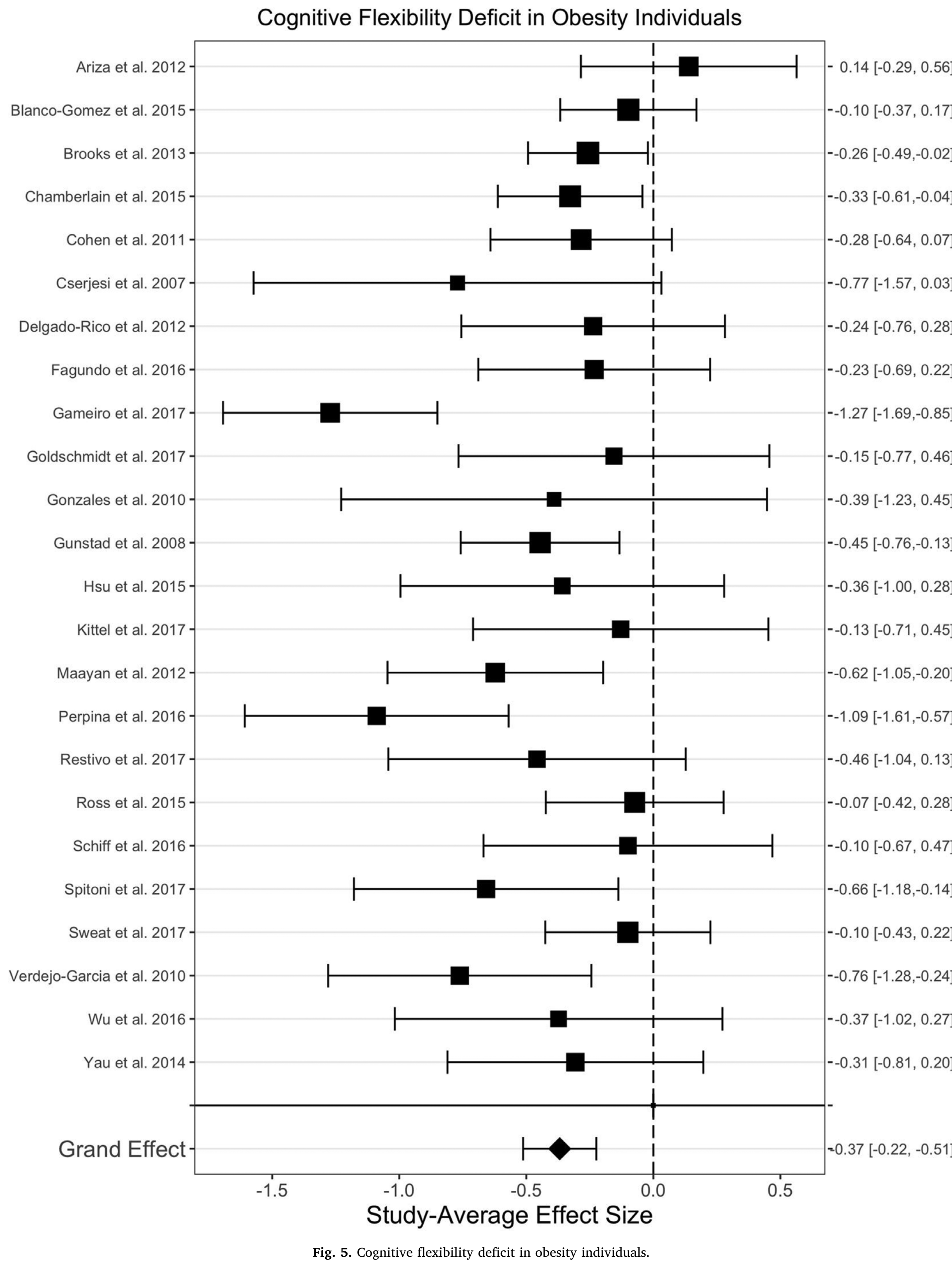

Fig. 5. Cognitive flexibility deficit in obesity individuals.

memory was driven by differences in the effect of obesity on the letter–number sequencing task compared to effects of obesity on other tasks, $B = 0.468$, $t(4.4) = 4$, $p = 0.013$. Thus, although relatively consistent across conditions, the effect of obesity on working memory is moderated by the task used to assess working memory, with less of an effect on the Letter–number sequencing task.

3.2.5. Decision-making

The analysis of studies examining differences between obese and healthy weight individuals in measures of decision-making ($m = 27$, $k = 46$) revealed a significant overall effect, $g^{+} = -0.441$, $t(25.7) = -6.82$, $p < 0.001$, 95% CI [-0.574, -0.308] (Fig. 7), such that obese participants performed worse than healthy weight participants on

Table 3
Moderator analyses for studies of cognitive flexibility in obesity.

Variable	β	t	F	m	g	df	p
Participant Age	−0.053	−0.92				7.4	0.389
Percent Female Participants	0.017	0.33				6.8	0.754
BMI (adult sample)	−0.127	−1.23				5.1	0.272
Measures of cognitive flexibility			0.92			12.6	0.425
Wisconsin Card Sorting Test				8	−0.532	6.9	0.036
Trail Making Test B/B-A				13	−0.312	10.1	0.002
Other				8	−0.395	6.5	0.014

Note: Significant ($p < 0.05$) moderating effects are listed in boldface font.

measures of decision-making. There was low heterogeneity across these studies' effects, $\tau^2 = 0.060$, indicating that the altered performance on decision-making is relatively consistent across various conditions.

Moderator analyses showed that age, percentage of female participants, and BMI did not significantly influence the pooled effect sizes (Table 5). However, the task used to assess decision-making significantly moderated effects of obesity on decision-making, $F(2, 13.6) = 4.51$, $p = 0.032$ (Table 5). Seven different tasks were used to assess decision-making in studies examining differences in decision-making between obese and healthy weight individuals. The most frequently used tasks were the Delay discounting task, and the Iowa gambling task. Eleven studies included the Delay discounting task, and obese participants performed worse on this task than healthy weight participants, $g^+ = -0.416$, 95% CI [−0.602, −0.231]. Twelve studies included Iowa gambling task, and obese participants performed worse on this task than healthy weight participants, $g^+ = -0.580$, 95% CI [−0.815, −0.344]. Seven studies included other measures of decision-making. Although obese participants performed worse on these other decision-making tasks than healthy weight participants, $g^+ = -0.200$, $t(4.2) = -2.87$, $p = 0.044$, the difference between obese and healthy weight participants in these other decision-making tasks was not as large as the difference in the Delay discounting and Iowa gambling tasks, $B = 0.352$, $t(7.8) = 2.97$, $p = 0.019$.

3.2.6. Verbal fluency

The analysis of studies examining differences between obese and healthy weight participants in verbal fluency ($m = 9$, $k = 12$) revealed a significant overall effect, $g^+ = -0.308$, $t(5.7) = -3.90$, $p = 0.009$, 95% CI [−0.504, −0.112] (Fig. 8), such that obese participants performed worse on measures of verbal fluency than healthy weight participants. There was low heterogeneity across these effects, $\tau^2 = 0.023$, indicating that the obesity-related performance impairment in verbal fluency was relatively consistent across various conditions. There were not enough studies or task variability within studies examining of effects of obesity on verbal fluency to conduct reliable moderator analyses.

3.2.7. Planning

The analysis of studies examining differences between obese and healthy weight participants in planning ($m = 6$, $k = 7$) revealed a significant overall effect, $g^+ = -0.346$, $t(4.5) = -3.08$, $p = 0.031$, 95% CI [−0.643, −0.048] (Fig. 9), such that obese participants performed worse than healthy weight participants on tasks assessing planning. There was low heterogeneity across these studies' effects, $\tau^2 = 0.036$, indicating that the impaired performance on planning is relatively consistent across various conditions. There were not enough studies or task variability within studies examining of effects of obesity on planning to conduct reliable moderator analyses.

3.3. Primary analyses of overweight effects

We first tested whether potential differences in executive functions between overweight and normal weight individuals were broad and nonspecific or whether any potential differences varied by executive function domain. Results indicated that differences in executive functions between overweight and normal weight individuals did not differ across the domains of inhibition, cognitive flexibility, working memory, decision-making, verbal fluency, and planning, $F(5, 3.97) = 0.70$, $p = 0.654$. Nonetheless, we present analyses of each executive function below.

The analysis of studies examining effects of overweight on inhibition ($m = 10$, $k = 20$) revealed a significant overall effect, $g^+ = -0.234$, $t(9.8) = -2.56$, $p = 0.029$, 95% CI [−0.438, −0.030] (Fig. 10), such that overweight participants performed worse on measures of inhibition than healthy weight participants. Similarly, the analysis of studies examining effects of overweight on working memory ($m = 8$, $k = 17$) also revealed a significant overall effect, $g^+ = -0.133$, $t(3.8) = -5.35$, $p = 0.007$, 95% CI [−0.204, −0.063] (Fig. 11), such that overweight participants performed worse on measures of working memory than healthy weight participants. There were not enough studies comparing executive functions of overweight to healthy weight participants to conduct moderator analyses.

Nonsignificant overall effects were founded when analyzing effect sizes on cognitive flexibility ($m = 6$, $k = 6$), $g^+ = -0.096$, $t(3.0) = -1.52$, $p = 0.227$, 95% CI [−0.299, 0.107], decision-making ($m = 6$, $k = 18$), $g^+ = -0.030$, $t(4.4) = -0.271$, $p = 0.838$, 95% CI [−0.397, 0.337], verbal fluency ($m = 3$, $k = 4$), $g^+ = -0.007$, $t(1.3) = -0.07$, $p = 0.952$, 95% CI [−0.739, 0.725], and planning ($m = 3$, $k = 4$), $g^+ = -0.323$, $t(2.9) = -1.81$, $p = 0.171$, 95% CI [−0.904, 0.258]. However, because of the small study set sizes, it is difficult to interpret these nonsignificant effects, especially in light of the nonsignificant F test examining differences in effects of overweight on executive functions.

4. Discussion

From resisting temptation to keeping long-term goals in mind, executive functions play a critical role in everyday life. However, despite the obvious relevance of executive functions to overweight and obesity, much is still unknown about executive function abilities in individuals with excess weight. We addressed this gap in the literature by conducting a meta-analysis of effects of obesity and overweight on inhibition, cognitive flexibility, working memory, decision-making, verbal fluency, and planning. Our meta-analysis indicated that obese individuals showed poorer executive functioning across all domains than healthy weight individuals. Unexpectedly, however, overweight participants only showed significant deficits in inhibition and working memory; no differences between overweight and healthy weight individuals emerged on tasks assessing cognitive flexibility, decision-making, verbal fluency, and planning. However, there were too few studies comparing overweight and healthy weight individuals on tasks assessing cognitive flexibility, decision-making, verbal fluency, and planning to make strong claims about the lack of significant differences between groups. Also unexpectedly, age, gender, BMI did not moderate effects of obesity on executive functions. Interestingly, though, the measures used to assess working memory and decision-making moderated effects of obesity on those executive functions. There were not enough studies of overweight individuals to examine moderators of those effects.

The observed magnitude of effect sizes testing differences in executive functions between obese/overweight individuals and normal weight controls resembles magnitudes found in previous reviews (Lavagnino et al., 2016a; Wu et al., 2016a). However, our meta-analysis extends the findings from previous reviews in several ways. First, we included a larger total sample of obese/overweight individuals. Second,

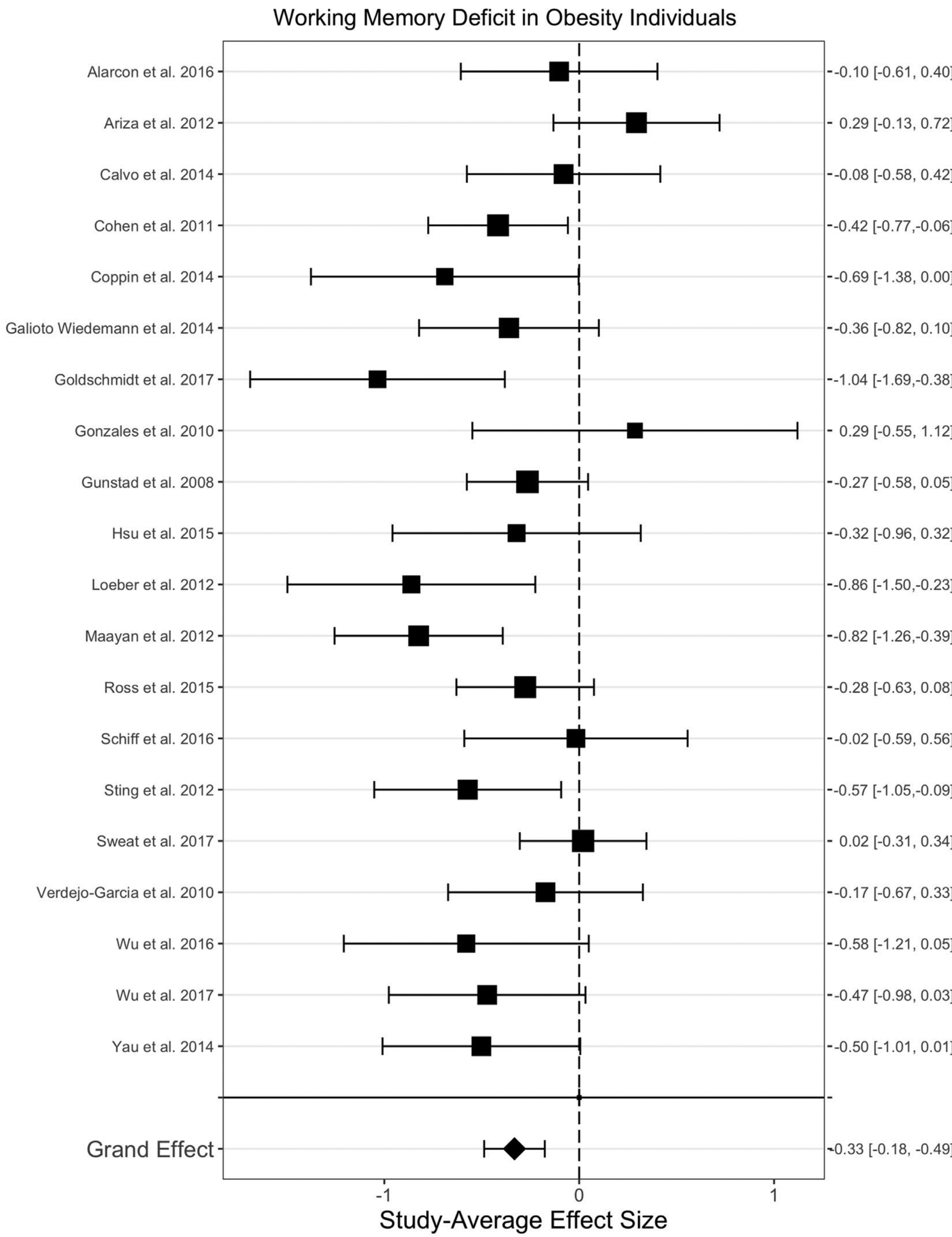

Fig. 6. Working memory deficit in obesity individuals.

extending previous meta-analyses that focused on one specific executive function (Wu et al., 2016a) or one selected executive function task (Lavagnino et al., 2016a), the present meta-analysis took a wider range of executive function measures into account to cover a broad spectrum of executive function in obese/overweight individuals. In addition, our review was the first to systematically summarize findings of altered inhibition, working memory, verbal fluency and planning in obese/overweight by means of meta-analysis. Finally, the current meta-analysis on executive functions differentiated between obese and overweight individuals. Of note, we found sufficient evidence for a broad impairment of executive functions in obese individuals, whereas there were not enough studies to make definitive inferences about the

Table 4
Moderator analyses for studies of working memory in obesity.

Variable	β	t	F	m	g	df	p
Participant Age	0.021	0.30				4.3	0.775
Percent Female Participants	−0.016	−0.28				7.0	0.791
BMI (adult sample)	0.105	0.99				4.3	0.377
Measures of working memory			**6.98**			**6.8**	**0.023**
Digit Span				6	−0.346	3.2	0.011
Letter–number sequencing				4	0.026	2.7	0.748
Other				12	−0.477	10.5	< 0.001

Note: Significant ($p < 0.05$) moderating effects are listed in boldface font.

breadth of executive function impairment in overweight.

Taken together, the findings of the present meta-analysis support the notion that obesity is associated with poor executive function. Past researchers have assumed or argued that clinical consequences of adiposity, such as hypertension, have an impact on cognition, which may explain this association. However, this hypothesis was not strongly supported by our results, as this meta-analysis included large young samples who were not likely to have cardiovascular disease. As such, it is possible that obesity itself may impair executive functioning. Specifically, some evidence indicates that obesity-related inflammatory activity may impair executive function in obese individuals (e.g., Bourassa and Sbarra, 2017; Lasselin et al., 2016). As might be inferred from the above, obesity is associated with sustained inflammatory activity, which originates from several factors (Capuron et al., 2017; Guillemot-Legris and Muccioli, 2017; Tilg and Moschen, 2006). In addition, data from several sources, including correlational (e.g., Bourassa and Sbarra, 2017), longitudinal (e.g., Trompet et al., 2008), experimental (e.g., Grigoleit et al., 2011), and genetic studies (e.g., Mooijaart et al., 2013), converge to suggest that heightened inflammatory activity contributes to poorer executive function (O'Brien et al., 2017; Shields et al., 2017). In sum, obesity-related inflammation may be one biological pathway involved in the link between obesity and poor executive function.

It is also possible that poor executive function is a risk factor for an increased BMI, indicating a bidirectional relationship between excess weight and executive function (Martin and Davidson, 2014; Smith et al., 2011; Stoeckel et al., 2017). The dual-process model argues that our behavior is determined by an interaction between the impulsive system and the executive control system (Strack and Deutsch, 2004). In the case of obesity, coupled with strong impulsive desires regarding high-calorie food and food cues, individuals who show a lack of control over these desires are particularly susceptible to obesity-related behaviors and outcomes (Ziauddeen et al., 2015). Indeed, both cross-sectional and longitudinal studies showed that lower executive function is associated with greater intake of fatty foods (e.g., Hall, 2012; Allom and Mullan, 2014; Powell et al., 2017), less intake of fruits and vegetables (e.g., Zhou et al., 2015; Wyckoff et al., 2017), poorer adherence to dietary intentions (e.g., Hall et al., 2008; Spitznagel et al., 2013), less physical activity (e.g., Riggs et al., 2010), higher BMI (e.g., Emery and Levine, 2017), weight gain (e.g., Nederkoorn et al., 2010; Nelson et al., 2016), and poor treatment outcomes during weight loss intervention (e.g., Witbracht et al., 2012). In sum, although obesity may itself impair executive function, much evidence indicates that poor executive function also contributes to excessive weight.

The weight-related impairments we observed in executive function are consistent with prior neuroimaging research, which has found altered connectivity among brain regions, structural abnormalities, and task related prefrontal cortical dysfunction (e.g., fronto-striato-parietal circuits) in obese individuals (e.g., García-García et al., 2013; Gearhardt et al., 2014). From a functional point of view, several studies have observed obesity-related hypoactivation in prefrontal cortical areas (e.g., inferior frontal gyrus) during performance of executive function tasks (e.g., go/no-go) (Batterink et al., 2010; Filbey and Yezhuvath, 2017; Hendrick et al., 2012). Similarly, obese individuals showed less activation of prefrontal regions (e.g., dlPFC, ventral lateral prefrontal cortex) than healthy weight individuals when trying to inhibit responses to high-calorie food stimuli (Batterink et al., 2010; Gearhardt et al., 2014; Silvers et al., 2014). In addition, excessive weight is related to lower functional connectivity in frontal-striatal networks during processing of food-related stimuli (García-García et al., 2013; Verdejo-Román et al., 2017). These results are also consistent with studies focusing on the structural differences between normal and obese individuals. That is, prior studies have found that obesity is related to lower volumes and cortical thickness in several subdivisions of the frontal cortex, including the superior frontal gyrus, middle frontal gyrus, inferior frontal gyrus, and orbitofrontal cortex (Brooks et al., 2013; Kurth et al., 2013; Marqués-Iturria et al., 2013; Pannacciulli et al., 2006; Taki et al., 2008; Walther et al., 2010; Wang et al., 2017). Importantly, reduced gray matter volume in the bilateral superior frontal gyrus was related to increased BMI at a 1-year follow-up (Yokum et al., 2012) and the negative relationship between cortical thickness in the right superior frontal gyrus and BMI was mediated by Stroop task performance (Lavagnino et al., 2016b). It is important to note that we could not test whether all of the weight-related impairments in executive function we observed were due to these known weight-related alterations in neural structure and function, but examining the neural correlates of the effects we observed is an exciting opportunity for future research.

4.1. Discussion of moderators

To further illuminate contextual factors that may influence the associations between excess weight and executive function, this meta-analysis examined the effects of potential moderators of these associations, including age, sex, BMI, and measures of executive function. Unexpectedly, however, age, gender, BMI did not moderate any effects of obesity we were able to test. This suggests that the associations between obesity and executive functions may be independent of these demographic factors. The lack of age effect on effects of weight on decision-making is different from what may have been expected based upon the result of the previous meta-analysis, which found non-significant overall decision-making effect size in adolescence (Wu et al., 2016a), given that we found an effect on decision-making. However, this difference may be due to differences in analytic strategy, as Wu and colleagues did not separate obese and overweight samples in their analyses.

We found that the measures used to assess respective executive functions moderated effects of obesity on working memory and decision-making. Studies using the letter-number sequencing task did not show significant effects of obesity on working memory, whereas studies using other working memory tasks, such as the digit span, showed significant deficits in obesity. Similarly, compared to the difference between obese and healthy weight participants in other decision-making tasks, larger effect sizes were observed in decision-making when either the delay discounting task or the Iowa gambling task were used. A possible explanation of this moderating effect might be to do with the sensitivity of the tasks used (Fitzpatrick et al., 2013). For example, the letter-number sequencing task may be insensitive to detecting subtle differences in working memory performance. However, these results must be interpreted with caution, as the mechanism(s) behind these task-specific effects in working memory and decision-making are currently unknown.

As mentioned earlier, there is some inconsistency in the literature describing associations between excessive weight and executive function. However, almost none of the potential moderating effects we examined in this meta-analysis emerged as significant. Inconsistences

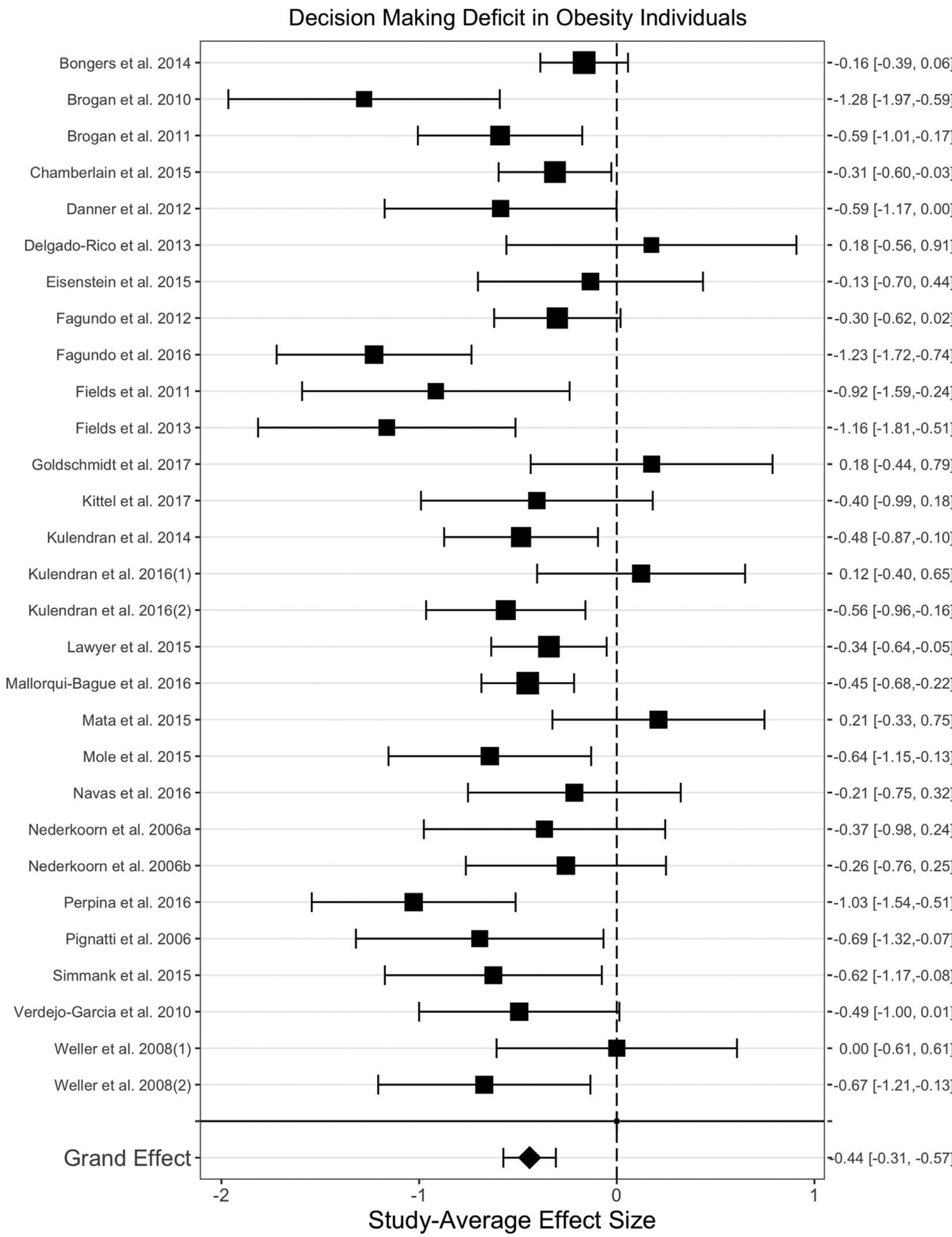

Fig. 7. Decision making deficit in obesity individuals.

across studies, such as heterogeneity in executive function tasks, may have obscured the emergence of moderating effects. For example, executive function tasks are likely to vary in sensitivity (Fitzpatrick et al., 2013). That is, some neuropsychological tasks are designed for use with brain-injured populations and thus are less sensitive to relatively subtle impairments in obese individuals than those designed to assess individual differences in the normal range. In addition, even in analyses of single tasks, task versions and dependent measures may vary, and in turn cause different sensitivities. Thus, we hesitate to draw conclusions about nonsignificant moderators given these and other between-study inconsistencies.

Table 5
Moderator analyses for studies of decision-making in obesity.

Variable	β	t	F	m	g	df	p
Participant Age	−0.107	−1.80				18.4	0.088
Percent Female Participants	−0.100	−1.69				6.7	0.138
BMI (adult sample)	−0.047	−0.59				7.8	0.573
Measure of decision-making			**4.51**			**13.6**	**0.032**
Delay Discounting Task				11	−0.416	10.6	< 0.001
The Iowa Gambling Task				12	−0.580	10.2	< 0.001
Other				7	−0.200	4.2	0.044

Note: Significant ($p < 0.05$) moderating effects are listed in boldface font.

4.2. Limitations and future directions

Despite its strengths, this meta-analysis has limitations. First, the small number of studies examining the association between obesity and verbal fluency or planning limited our ability to make inferences about effects of obesity on these executive functions, especially with regard to moderators. As such, when more studies examine verbal fluency or planning ability in obese individuals, an additional meta-analysis of these associations will be warranted. In addition, the effects on cognitive flexibility, decision making, verbal fluency and planning in overweight also need be interpreted with due caution due to the limited number of original studies. Second, there may be moderators of the associations between obesity and executive functions that are unaccounted for in our analyses. Some studies failed to report important information, such as clinical status of participants, education, economic status, whether participants took any obesity-treating medication, or if the participants had a psychiatric disorder, precluding moderator analyses on these variables. As a result, we could not explain the high heterogeneity in subgroup analysis of studies using Wisconsin Card Sorting Test and moderate heterogeneity in subgroup analysis of studies using Stop Signal Task. In addition, limited number of studies investigated obese individuals with a BMI over 40, which may underestimate the moderating effect of BMI. As such, we do not claim to present a complete picture of moderators of the associations between obesity and executive functions. Indeed, future large-scale studies assessing executive functions in obese/overweight individuals should therefore provide a full characterization of the participants and explore whether additional factors moderate effects of excessive weight on executive function. Third, although four studies in the obese sample also included some overweight individuals, we classified these samples as obese due to the group's average BMI. However, it is possible that including these studies in analyses may have underestimated true effect sizes. Although analyses suggest against this possibility, we note here that our results should be considered to be a conservative estimate of the association between obesity and executive function. Additionally, we recommend future studies clearly select participants and avoid including overweight and obese individuals in the same group. Fourth, obesity was operationalized via BMI in this meta-analysis, which is a relatively coarse measure of body density and may overlook relevant physical characteristics, such as body fat and anthropometric features (World Health Organization, 2011). Fifth, we were not able to examine the potential role of food stimuli in moderating effects of the association between obesity and executive function. Although we initially coded this variable in our dataset, only five studies used an executive function task that included food content—across all types of executive function tasks. As such, we were unable to analyze the contribution of this variable. Thus, future research could examine whether the association between obesity and executive function differs by varying stimuli used in the executive function tasks. What's more, although we have uncovered associations between obesity/overweight and poor executive functions, the studies included were cross-sectional. There is a relative lack of longitudinal studies to investigate whether altered EF is a risk factor or a consequence of obesity/overweight. Thus, more research is needed to investigate causal links between excessive weight and executive function. Finally, although a thorough search was conducted for unpublished studies, because we did not send unsolicited requests to researchers who had published other studies in the field that asked for them to provide data from unpublished studies, it is possible that some unpublished data were not included missed.

5. Conclusion

In conclusion, we found evidence to support the presence of broad executive function deficits in obese participants compared to healthy weight controls. In addition, overweight participants showed significant deficits on inhibition and working memory and nonsignificant deficits on cognitive flexibility, decision-making, verbal fluency, and planning performance compared to healthy weight controls. Age, gender, BMI did not moderate effects of obesity on executive function. However, the measures used to assess respective executive functions emerged as significant moderators of effects of obesity on working memory and decision-making. Research aimed at determining the causal mechanisms underlying associations between excessive weight and executive functions, as well as effects of executive function interventions on weight status in obese/overweight individuals, deserve further attention because of their important public health implications.

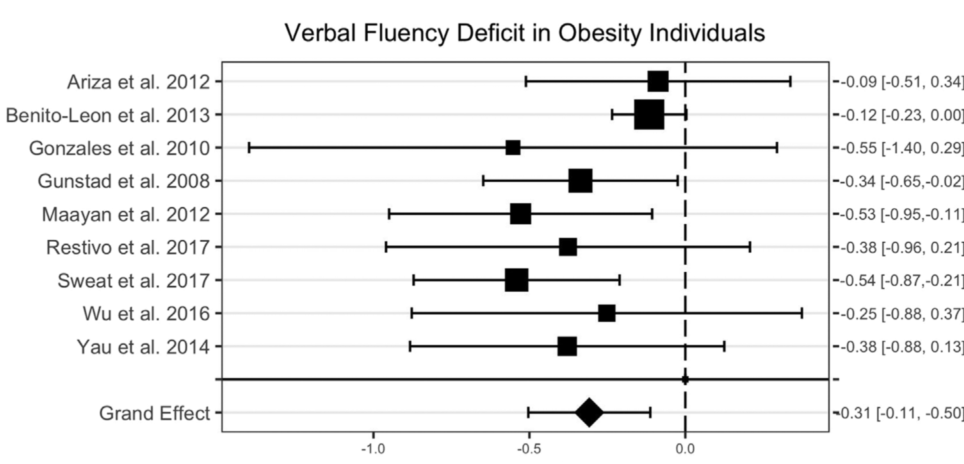

Fig. 8. Verbal fluency deficit in obesity individuals.

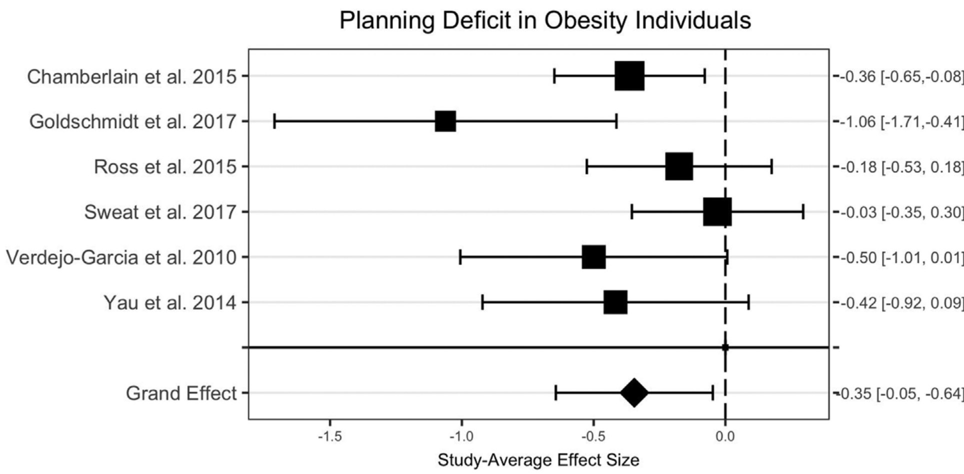

Fig. 9. Planning deficit in obesity individuals.

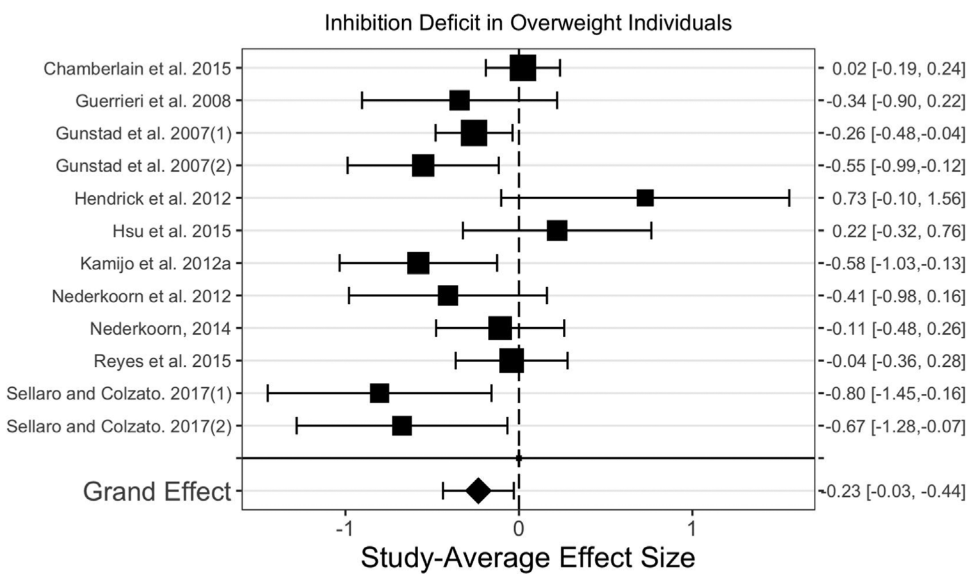

Fig. 10. Inhibition deficit in overweight individuals.

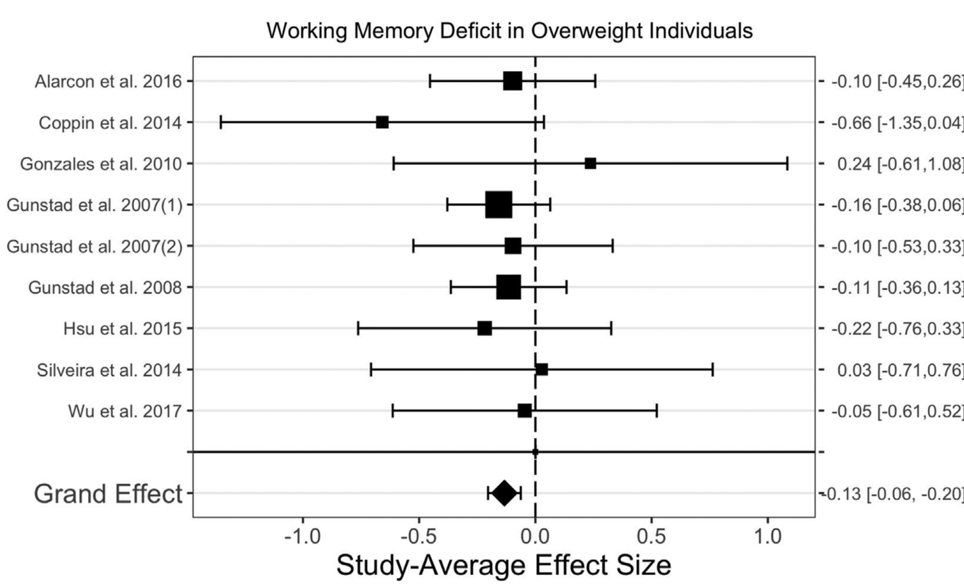

Fig. 11. Working memory deficit in overweight individuals.

Author contributions

Yingkai Yang, Cheng Guo and Yanling Liu developed the concept for this article and wrote the manuscript, Grant S. Shields provided critical revisions to the paper, and all authors read and approved the final version.

Declaration of conflicting interests

The authors declare that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.neubiorev.2017.11.020.

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