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Review

Child executive function and future externalizing and internalizing problems: A meta-analysis of prospective longitudinal studies

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ABSTRACT

To determine the association between executive function and later externalizing and internalizing problems, we conducted a meta-analysis of 167 studies (1098 effect sizes, total $N = 66{,}119$) that explored the longitudinal associations between executive functions in children and subsequent externalizing and internalizing problems. The results indicated that greater child executive function was prospectively associated with fewer attention-deficit/hyperactivity disorder (ADHD) symptoms, fewer conduct problems, fewer oppositional defiant disorder symptoms, less substance use, fewer broad externalizing problems, fewer depression symptoms, and fewer broad internalizing problems, but not with subsequent anxiety symptoms. Moderator analyses revealed that the sample type moderated the associations of executive function with both ADHD symptoms and conduct problems. Age of assessment moderated the association with broad externalizing problems, and executive function context moderated associations with both substance use and broad internalizing problems. These findings suggest that executive function in children prospectively predicts numerous externalizing and internalizing behaviors, suggesting that executive function may be an important target for psychopathology prevention programs and interventions.

Behavior problems are frequently dichotomized into two broad classes: externalizing and internalizing problems (e.g., Achenbach, Ivanova, Rescorla, Turner, & Althoff, 2016). Externalizing problems refer to individuals' negative or maladaptive behaviors directed toward one's environment, such as attention-deficit/hyperactivity disorder (ADHD) symptoms, oppositional defiant disorder (ODD) symptoms, conduct problems, or substance use (Beauchaine, Zisner, & Sauder, 2017; Hinshaw, 2002), while internalizing problems incorporate a variety of internally focused problems, such as anxiety or depression symptoms (Snyder & Hankin, 2016). Behavior problems are prevalent in school-age children (Merikangas et al., 2010) and are associated with a range of negative outcomes, including poorer academic performance (e.g., Vaillancourt, Brittain, McDougall, & Duku, 2013), peer difficulties (e.g., Henricsson & Rydell, 2006), and risky sexual behavior (e.g., Timmermans, van Lier, & Koot, 2008). Over long periods of time, behavior problems in children[1] may culminate in adverse outcomes, such as mental health disorders (e.g., Caspi, Moffitt, Newman, & Silva, 1996), and they may even contribute to early mortality (e.g., Jokela, Ferrie, & Kivimaki, 2009). Identifying factors that influence the development of these behaviors is thus an important goal for public health (Hentges et al., 2020).

1. Executive function

One important factor that may influence the development of internalizing or externalizing problems is executive function (Diamond & Ling, 2016). Executive function refers to the set of higher cognitive processes that enable planning and goal-directed control over thoughts,

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[1] [1]The words "child" and "children" in the current manuscript refer to both children and adolescents.

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emotions, and actions (Diamond, 2013). Executive function is typically thought to be underpinned by three component processes (Diamond, 2013): the first of these, inhibitory control, refers to the ability to suppress impulsive or automatic responses. A common task used to assess inhibitory control in children is the day and night task (Gerstadt, Hong, & Diamond, 1994), which requires children to respond with "night" to a picture of the sun, and "day" to a picture of the moon. The second of these component processes, working memory, refers to the ability to hold information in mind and manipulate it. A common task used to assess working memory in children is the digit span backward task (Garon, Bryson, & Smith, 2008), which requires children to repeat lists of digits backwards. The third component process underpinning executive function task performance is cognitive flexibility, which refers to the ability to shift attention as well as mental sets or rules when situationally appropriate. A common task used to assess cognitive flexibility in children is the dimensional change card sort task (Doebel & Zelazo, 2015). In this task, children sort bivalent cards one way (e.g., by color) and then are instructed to switch and sort the same cards a new way (e.g., by shape). Although inhibition, cognitive flexibility, and working memory are important aspects of executive function, they may not be the only cognitive processes that reflect executive functioning (e.g., Snyder, 2013; Snyder, Miyake, & Hankin, 2015). Indeed, several other skills that rely on executive functioning have been well defined in the literature (e.g., Lezak, Howieson, Loring, & Fischer, 2012), including (a) verbal fluency, 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 (e.g., Troyer, Moscovitch, & Winocur, 1997), and (b) planning, defined as formulating, evaluating, and selecting a sequence of thoughts and actions to achieve a goal (e.g., Lezak et al., 2012).

Additionally, executive function is also thought to vary along a continuum from "cool" (e.g., typical cognitive tasks) to "hot" (e.g., cognitive tasks with a reward) (Zelazo, 2020). Inhibitory control, cognitive flexibility, working memory, verbal fluency and planning are usually considered cool executive function skills, in that are typically measured using abstract, emotionally neutral tasks (e.g., day and night task), and they are associated with neural networks involving lateral parts of the prefrontal cortex (PFC) (Swick, Ashley, & Turken, 2011). In contrast, hot executive function involves goal-directed control elicited in motivationally or emotionally salient situations, and it relies more on the ventromedial PFC (Zelazo, 2020). Typical measures of hot executive function require participants to flexibly (re-)appraise whether to approach or avoid a rewarding stimulus. For example, in the delay of gratification task, children must postpone a salient immediate reward (e.g., a cookie) in favor of a less salient delayed reward (e.g., two cookies) (Mischel, Shoda, & Rodriguez, 1989).

1.1. Executive function and behavior problems

Recent conceptual models have suggested that an executive function deficit is an underlying risk factor for the development of behavior problems (e.g., Beauchaine et al., 2017; Eisenberg, Spinrad, & Eggum, 2010; Hankin et al., 2016; Lynch, Sunderland, Newton, & Chapman, 2021; Nelson et al., 2019; Snyder et al., 2015; Snyder, Friedman, & Hankin, 2019; Zelazo, 2020). In reviewing research on the development of executive function skills, Zelazo (2020) proposed three reasons why executive function difficulties are related to the development of behavior problems. First, executive function skills play a fundamental role in flexibly adapting to changing circumstances. Dysfunctional use of these skills, therefore, may have widespread negative behavioral consequences, such as externalizing and internalizing problems. Second, the hierarchical nature of both executive function skills and the neural networks (e.g., PFC) that support them render them particularly vulnerable to disturbances (e.g., early life adversity). Third, the long developmental period of executive function skills might leave them vulnerable to interruption from a wide scope of influences (Diamond, 2013), such as stress (e.g., Shields et al., 2020; Shields, Deer, Hastings, & Hostinar, 2021; Shields, Ivory, & Telzer, 2019).

Poor executive function during childhood may also lead to later behavioral problems directly via poorer attentional, emotional, and behavioral control (Nelson et al., 2019). In particular, externalizing problems involve difficulty controlling emotion (e.g., anger) or inappropriate behaviors (e.g., aggression) (American Psychiatric Association, 2013). Better attention and emotional control both allow children to modulate affective arousal, integrate information, and plan, and better behavioral control allows children to curb inappropriate behaviors (Eisenberg et al., 2004). Similarly, internalizing behaviors (e.g., depression/anxiety symptoms) often involve difficulties in controlling attention or emotion (e.g., distress). Better attentional and emotional control support the ability to disengage from negative thoughts or threatening stimuli, thereby reducing negative biases in attention and memory, and improving top-down regulation of negative emotions (e.g., Koster, De Lissnyder, Derakshan, & De Raedt, 2011). In short, better executive function during childhood may protect against in the development of problem behaviors via better attentional, emotional, and behavioral control.

Coming from a different perspective, Carver and colleagues have also suggested that poor executive function is linked to behavior problems because inhibitory control (one of the core executive functions) supports the regulation of emotions (e.g., Carver, Johnson, & Timpano, 2017). According to their model, a combination of low incentive sensitivity and low inhibitory control of emotions will render people vulnerable to internalizing symptoms, such as sadness. In contrast, vulnerability to externalizing symptoms, such as aggression, might result from a combination of high incentive sensitivity and low inhibitory control over emotions.

Together, the aforementioned models each suggest a critical role of executive function in the development of internalizing and externalizing behaviors or symptoms. However, it is also possible that behavior problems could impair executive function over time (Maasalo, Lindblom, Kiviruusu, Santalahti, & Aronen, 2020). For example, depression and anxiety might themselves increase allostatic load (e.g., upregulating pro-inflammatory activity), disrupt the PFC, and thereby adversely impact executive function (Shields, Moons, & Slavich, 2017). Similarly, early externalizing behaviors, such as aggression, might indirectly lead to worse executive function via reducing children's involvement in social activities that promote the learning of strategies to improve inhibitory control or cognitive flexibility (Hughes, Devine, Mesman, & Blair, 2020; Hughes & Ensor, 2008). However, relatively little work to date has explored this hypothesis in children (but see: Donati, Meaburn, & Dumontheil, 2021; Friedman, du Pont, Corley, & Hewitt, 2018; Hughes et al., 2020; Kahle, Utendale, Widaman, & Hastings, 2018; Maasalo et al., 2020; Mac Giollabhui et al., 2020; Quistberg & Mueller, 2020; Romer & Pizzagalli, 2021). In contrast, numerous studies have examined whether childhood executive function deficits predict the development of future behavior problems, and—given heterogeneity within the literature, described below—a meta-analysis of these prospective studies is warranted.

1.2. Potential moderators of the relation of executive function to behavior problems

Although the above theories have described pathways through which childhood executive function may relate to behavior problems over time, there have been some inconsistencies in the related literature. To understand the source of these inconsistencies, it will likely be important to examine potential moderators of the association between childhood executive function and later behavior problems. For clarity, we categorize factors that have been proposed to account for heterogeneity and inconsistency in associations of child executive function with behavior problems as either participant/sample variables or study design variables.

The participant/sample variables with the strongest evidence for

moderating the associations between childhood executive function and later behavior problems are the age of the child at the time of assessment of executive function, sex, and sample type. During the first few years of life, children's executive functions are not yet well developed (Garon et al., 2008). As children become older and the stability of measures of executive function improves, the relations between executive function and behavior problems should be better established and easier to detect. Regarding sex, some research has suggested that girls may have better or more effective executive function than boys (e.g., Rubia et al., 2013). Similarly, sex differences in externalizing and internalizing problems have also been reported: boys are more prone to externalizing problems (Leadbeater, Kuperminc, Blatt, & Hertzog, 1999), and girls are more prone to internalizing problems, especially in adolescence (Zahn-Waxler, Klimes-Dougan, & Slattery, 2000). One might therefore expect relations between executive functions and problem behaviors to differ between boys and girls, and there is some evidence for this idea (e.g., Schoemaker, Mulder, Dekovic, & Matthys, 2013; van Deurzen et al., 2012). Finally, there is also reason to examine the effect of sample type (i.e., nonclinical, mixed, or clinical sample), as some work has found that the associations of executive function with problem behaviors such as externalizing problems were numerically stronger in mixed or clinical samples than in nonclinical samples (e.g., Lin & Gau, 2019; White et al., 2017).

As for study design variables that might moderate associations between executive function and behavior problems, one potentially important design factor that varies across studies is whether the executive function task is hot or cool (i.e., the context of executive function task). There is some evidence that hot, but not cool, executive function relates to behavior problems, especially externalizing problems (e.g., Backer-Grondahl, Naerde, & Idsoe, 2019; Willoughby, Kupersmidt, Voegler-Lee, & Bryant, 2011). In addition, there is also evidence that the component of executive function assessed (e.g., inhibitory control, working memory, or cognitive flexibility) can impact associations of executive function with behavior problems. For example, some work has found that inhibitory control was more strongly associated with some behavior problems (e.g., externalizing problems) than working memory or cognitive flexibility (e.g., Brocki, Nyberg, Thorell, & Bohlin, 2007; Schoemaker et al., 2013). Further, the modality of problem behavior assessment (e.g., teacher-report, parent-report, or self-report) may also moderate links between executive function and behavior problems. For example, one study found that executive function was related to teacher-reported problem behaviors, but not parent-reported problem behaviors (Backer-Grondahl et al., 2019). Finally, time span between executive function and problem behavior assessments might moderate associations between those variables, though this variable has not been directly examined in prior work.

1.3. Previous meta-analyses

Previous meta-analyses have been conducted on executive function (and related concepts) in relation to some behavior problems. For example, many meta-analyses have found executive function impairments in various forms of psychopathology (e.g., Abramovitch, Short, & Schweiger, 2021). However, most of these meta-analyses have focused on studies that used case-control designs in clinical samples, which leaves open the question about links between executive function and these behaviors in nonclinical samples. One meta-analysis, however, did find that executive function impairments in children were associated with general externalizing behavior problems in both community and clinical samples (Schoemaker et al., 2013). Importantly, all of these included studies in this work used cross-sectional designs, so the longitudinal association between executive function and the development of those forms of psychopathology could not be assessed in those meta-analyses.

In short, although excellent meta-analyses have examined links between executive function and problem behaviors in case-control and cross-sectional designs in clinical samples, to date no meta-analysis has examined the prospective relationship between executive function in childhood and later internalizing and externalizing problems. Without such a meta-analysis, much of the conflicting findings in the literature cannot be resolved, and it is therefore still unknown whether executive function deficits in children is a risk factor for future externalizing and internalizing problems, and if so, what factors might moderate that association. A meta-analysis of prospective studies would therefore provide critically important information that may help guide the development of preventive interventions.

1.4. The current meta-analysis

To address these issues, we conducted the first meta-analysis, to our knowledge, of prospective longitudinal studies that examined the associations between childhood executive function and subsequent externalizing and internalizing problems. We focused on 8 behavior problem types: ADHD symptoms, conduct problems, ODD symptoms, substance use, broad externalizing problems, depression symptoms, anxiety symptoms, and broad internalizing problems. In addition, we investigated 7 factors that could potentially moderate associations between executive function and various behavior problems: age at the time of executive function assessment, sex, sample type, the length of time between executive function and problem behavior assessment, the context in which executive function was used (i.e., hot vs. cool tasks), component of executive function (e.g., inhibitory control, working memory, or cognitive flexibility), and behavior measure informant (e.g., self, parent, teacher). This work thus addresses the critical questions of whether childhood executive function is a predictor of future behavior problems, and under what circumstances is this association strongest.

2. Methods

2.1. Literature review

The current meta-analysis was performed according to the Preferred Reporting Items for Systematic reviews and Meta Analyses guidelines (Appendix A). A protocol for this work was registered on the Open Science Framework (OSF: https://osf.io/wntdr). To obtain studies for use in the meta-analysis, we performed a comprehensive search in the databases PubMed, ISI Web of Knowledge, PsycINFO, and ProQuest Dissertations and Theses using the search string presented in the Appendix B. We concluded this search in April 2021, and we conducted an updated search in April 2022 to ensure that all current studies were included between the 2021 and the period. 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 ensure that our review was comprehensive, we conducted numerous nonexhaustive searches of Google Scholar using simple strings, such as ("executive function" AND "behavior problems"). Further, the forward and backward citations of all eligible papers were hand-searched for relevant studies. Fig. 1 shows the flow diagram.

2.2. Inclusion criteria

Studies were incorporated into this meta-analysis if they were available in English, studied human participants, used a longitudinal design to assess the relation between at least one task known or shown to depend upon or assess executive function in children (mean age below 18), had at least one measure of behavior problems, and provided data or statistical information that allowed for effect size calculation. If an article did not include sufficient information for effect size analysis, we contacted the corresponding authors of those articles to obtain the necessary details. If the corresponding author did not respond, the study was excluded. Further, we excluded 1 article using emotional faces in the executive function task (highly different from all included articles in

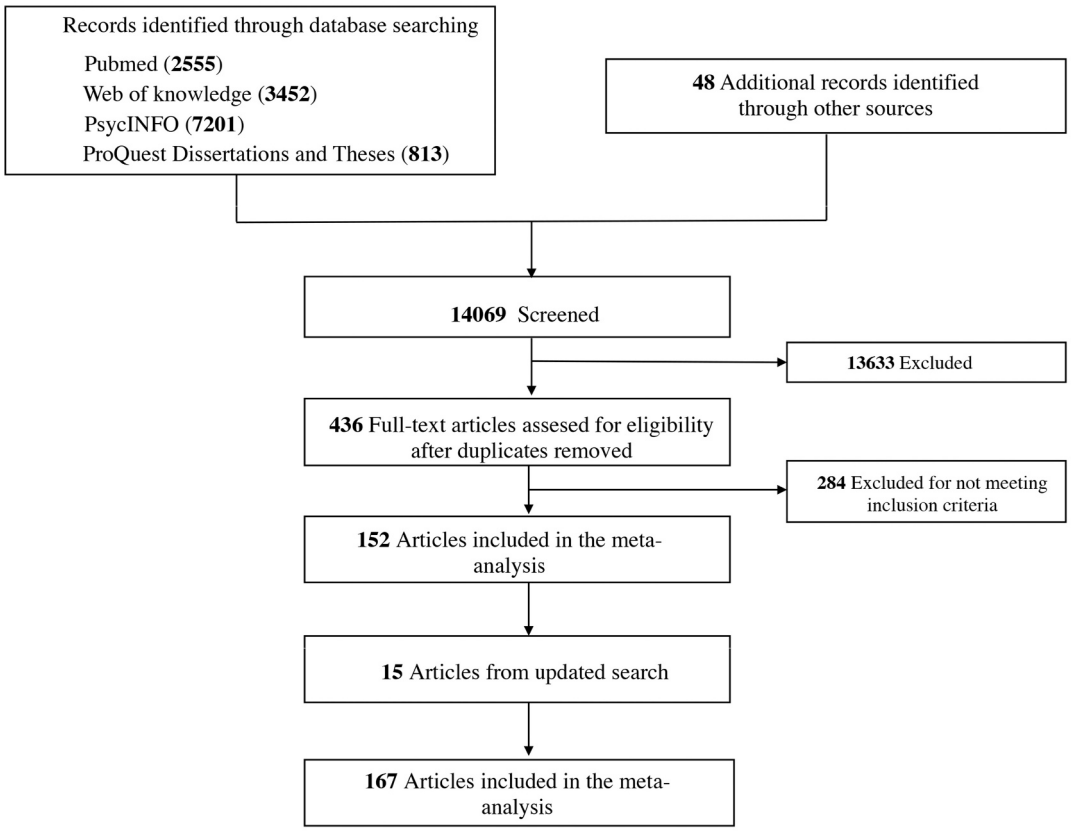

Fig. 1. Flow diagram illustrating the process of our review, screening, and article selections.

current work). Finally, it should be noted that it is common for multiple papers to use the same dataset (e.g., National Institute of Children Health and Development [NICHD], dataset) in longitudinal research. We included these studies using the same dataset only if they reported nonoverlapping measures or different participant ages, and we coded these effect sizes as coming from the same study. The first author screened the full texts and extracted data from the selected studies, and the third and fourth authors checked the data for accuracy. Percent agreement was very good (e.g., >95%). All discrepancies were settled through discussion.

2.3. Coding of studies and moderators

We coded eight behavior problems as outcomes: ADHD symptoms (inattention, hyperactive, and/or combined), conduct problems (i.e., symptoms of conduct disorder, or measures of antisocial behavior, delinquency, aggression, or rule-breaking behavior), ODD symptoms (symptoms of oppositional defiant disorder), substance use (i.e., measures of drugs, alcohol, or cigarettes use), depression symptoms, anxiety symptoms, broad externalizing problems (i.e., combination measures including two or more of ADHD symptoms, ODD symptoms, and conduct problems), and broad internalizing problems (i.e., measures of combinations of depression symptoms, anxiety symptoms, social withdraw, or somatic complaint, or more broad measures of emotional symptoms, social stress, low energy, loneliness, peer relationship problems, low self-perception, or low self-esteem).

The context of the executive function task was coded as "cool" if the task used abstract or neutral materials, whereas it was coded as "hot" if the task involved a reward. When a study created a *Z*-score composite of cool and hot executive function from both cool and hot executive function tasks (e.g., the study created a composite score by standardizing and averaging together the go/no-go and a snack delay task) and did not provide the results at the level of individual tasks, we coded the study as mixed (See Appendix C for a complete description of task coding).

The component of executive function (for cool executive function tasks; Shields, Sazma, & Yonelinas, 2016; Yang, Shields, Guo, & Liu, 2018) was coded as inhibitory control, cognitive flexibility, working memory, planning, or verbal fluency, and codings were derived from empirical or theoretical work suggesting that a given task primarily utilized the particular coded executive function. When a study created a Z-score composite of executive function from two or more executive function tasks (e.g., the study created an executive function composite by Z-scoring and averaging together the *n*-back and the go/no-go) and did not present the results at the level of individual tasks, we coded the study as mixed (See Appendix C for a complete description of task coding).

Age at the time of executive function assessment, sex (percent of the study sample that was female), and the length of time (in years) between executive function and problem behavior assessments were coded as continuous moderators. Sample type was coded as general, mixed (e.g., participants with elevated behavior problems such as T score above 60 were oversampled, or studies that grouped individuals with and without clinically significant behavior problems together), at-risk (e.g., samples from low-income families), or clinical (e.g., all participants had clinically significant behavior problems). The behavior measure informant was coded as parent(s)-report, teacher-report, self-report, or mixed.

2.4. Analytic strategy

The correlation coefficient (*r*) was used as the effect size metric of interest. Most studies provided information on non-adjusted effects with *r*, though a minority of studies provided adjusted effect sizes with $r_{partial}$ (e.g., ten studies), a standardized regression coefficient (e.g., twenty-five studies), or an odds ratio (e.g., four studies). Standardized regression coefficients were transformed to *r* using the formula $r = \beta + 0.05\ \lambda$,

where λ is an indicator variable that equals 1 when β is non-negative and 0 when β is negative (Peterson & Brown, 2005). Odds ratios were transformed to r using the hausekeep package in R, version 3.6.2 (R Project for Statistical Computing). Correlation coefficients were transformed to z-scores using the Fisher z transformation, then meta-analyzed to obtain both a point estimate and its 95% CI. To facilitate interpretation of the results, following the analyses, Fisher's z scores were then back-transformed to a correlation using the Fisher z-to-r transformation.

It should be noted that most studies reported more than one outcome (e.g., outcomes on different executive function tasks or time spans, different outcomes from the same study sample). 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 (Borenstein, Hedges, Higgins, & Rothstein, 2009; Scammacca, Roberts, & Stuebing, 2014). Thus, we employed the meta-analytic technique of robust variance estimation to account for dependence between effect size estimates (Hedges, Tipton, & Johnson, 2010; Tanner-Smith & Tipton, 2014). This technique robustly estimates effect size weights and standard errors for the given effects, allowing for multiple outcomes within studies. We used the robumeta package in R 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 & Tipton, 2014). Heterogeneity was quantified as τ^2, which represents between-study variance in this meta-analytic method (Borenstein, Higgins, Hedges, & Rothstein, 2017). We only conducted moderator analyses for outcomes in which there were at least 10 samples and a minimum cell size of samples >5 for each categorical comparison (Borenstein et al., 2009).

For all of the following analyses, a positive effect size indicates that higher child baseline executive function is related to more future behavior problems, whereas a negative effect size indicates that higher child baseline executive function is related to less future behavior problems. In addition, if the coefficient for a continuous moderator is significant, it means that as the continuous variable increases or decreases, the association between child executive function and problem behavior increases or decreases.

2.5. Quality assessment

We assessed the quality of included studies using nine items adapted from a previously published systematic review of longitudinal studies (Tang, Werner-Seidler, Torok, Mackinnon, & Christensen, 2021). See Appendix D for further details of the quality assessment.

3. Results

3.1. Search results

The initial search identified 14,069 records. We screened the full-text of 436 manuscripts, and 167 studies were included in the final analyses according to inclusion criteria (Fig. 1). The included studies are described in Appendix E.

3.2. Preliminary analyses

3.2.1. Study characteristics

The full study sample included 167 studies (see Appendix F), 112 independent samples (i.e., total $m = 112$), and 66,119 participants (i.e., total $N = 66{,}119$). From these studies, we obtained 1098 effect sizes (i.e., total $k = 1098$), which is similar to the number of effect sizes per study obtained in similar meta-analyses (e.g., Scammacca et al., 2014; Shields, Bonner, & Moons, 2015).

Among studies examining associations of executive function with externalizing or internalizing problems, associations with ADHD symptoms were examined in 32 independent samples including 10,688 individuals, associations with conduct problems were examined in 46 independent samples including 19,356 individuals, associations with ODD symptoms were examined in 6 independent samples including 4684 individuals, associations with substance use were examined in 24 independent samples including 15,231 individuals, associations with broad externalizing problems were examined in 21 independent samples including 26,184 individuals, associations with depression symptoms were examined in 19 independent samples including 11,819 individuals, associations with anxiety symptoms were examined in 12 independent samples including 6625 individuals, and associations with broad internalizing problems were examined in 28 independent samples including 32,383 individuals.

3.2.2. Publication bias

To assess publication bias, we conducted the Egger test for funnel plot asymmetry for each outcome (see Fig. S1 in Appendix G). Egger's test was nonsignificant for ADHD symptoms ($t(30) = -1.45$, $P = .16$), conduct problems ($t(44) = -0.83$, $P = .41$), ODD symptoms ($t(4) = -0.25$, $P = .81$), substance use ($t(22) = 0.13$, $P = .90$), depression symptoms ($t(17) = 0.34$, $P = .74$), and anxiety symptoms ($t(10) = -0.43$, $P = .68$), indicating a lack of evidence for publication bias in these associations. There was, however, evidence for publication bias in broad externalizing problems ($t(19) = 3.88$, $P = .001$), and broad internalizing problems ($t(26) = 2.13$, $P = .043$). Estimates indicate that negative associations between executive function and broad externalizing problems and broad internalizing problems were published disproportionately more than null or positive associations. As such, we conducted trim and fill analyses. The trim and fill analysis for broad internalizing problems did not estimate any missing studies (estimated missing = 0; $SE = 3.22$), indicating that Egger's test for publication bias may have overestimated publication bias for broad internalizing problems. The trim and fill analysis estimated that four unpublished studies were missing from analyses of broad externalizing problems (estimated missing = 4; $SE = 3.08$). Although the actual overall association was numerically weaker than what is reported in the analysis below, the overall estimated association with broad externalizing problems was still significant when including the estimated missing studies ($P < .001$). Thus, despite some evidence for publication bias, the trim and fill analyses suggest that the association of executive function with broad externalizing problems and broad internalizing problems are significant and in the same direction as below.

3.2.3. Main meta-analysis results

Results of meta-analyses for each problem behavior are presented below. Each of the following meta-analyses showed low between-study heterogeneity ($\tau^2 < 0.02$), indicating that the associations were relatively consistent across studies and conditions. Below we describe which factors significantly moderated associations between executive function and externalizing and internalizing problems. Any moderators not mentioned below were nonsignificant (see Tables S1-S7 in Appendix H for all the results of the moderator analyses, including analyses examining specific executive function domains or components).

3.2.4. Attention-deficit/hyperactivity disorder symptoms

The meta-analysis of the association with ADHD symptoms ($m = 32$, $k = 217$, $N = 10{,}688$) produced a significant effect size (r) of −0.19 (95% CI, −0.23 to −0.14; $t_{30.2} = -9.10$, $P < .001$) (Fig. 2), indicating that poorer executive function during childhood was associated with more ADHD symptoms later in life.

Sample type emerged as a significant moderator of this association, $F(2, 14.4) = 6.07$, $P = .012$. In particular, child baseline executive function was more strongly associated with subsequent ADHD symptoms in mixed ($r = -0.24$, 95% CI, −0.30 to −0.18; $t_{12.4} = -8.20$, $P < .001$) and at-risk populations ($r = -0.24$, 95% CI, −0.30 to −0.17; $t_{5.0} =$

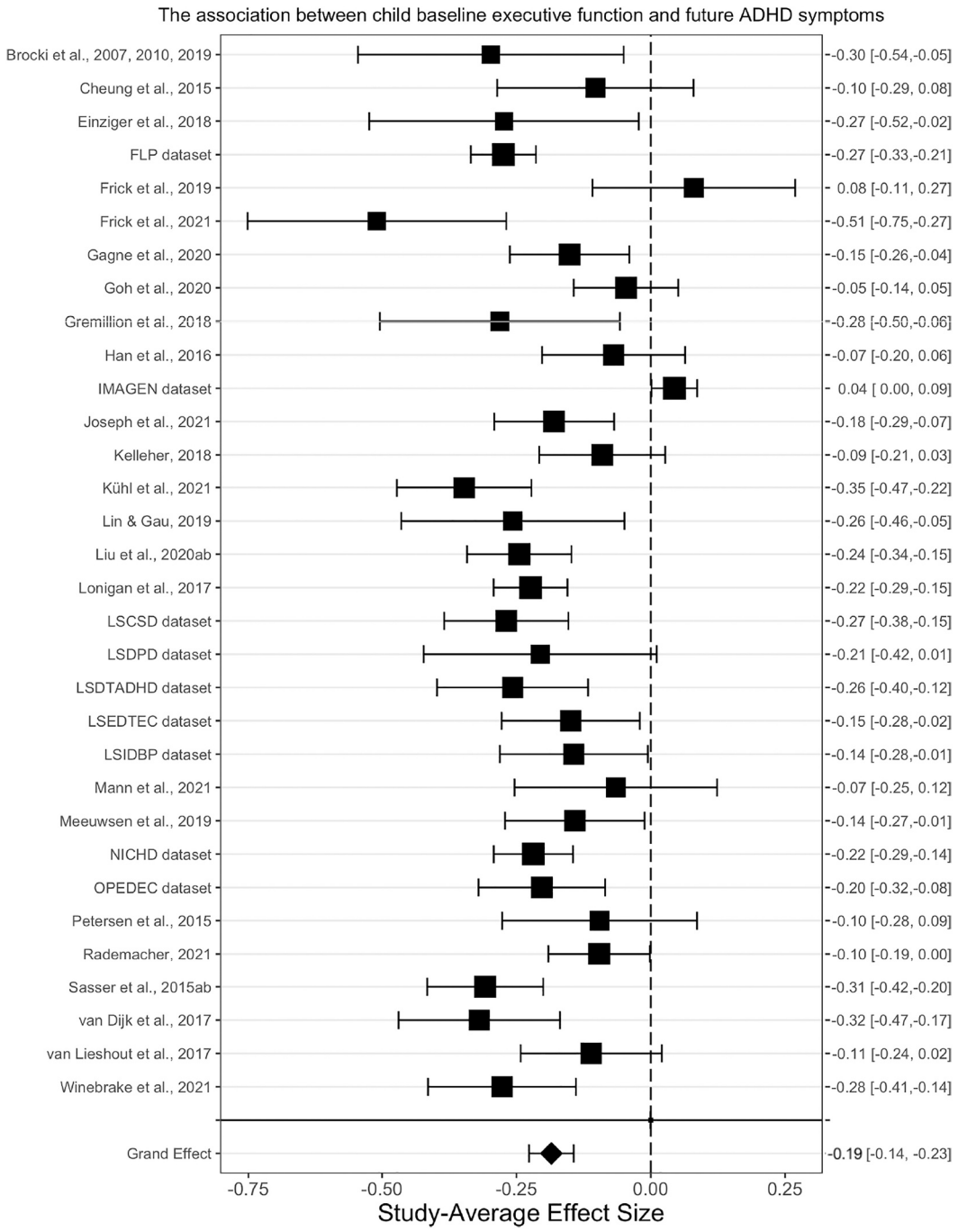

Fig. 2. Forest plot depicting study-average association between child baseline executive function and subsequent ADHD symptoms.

−9.75, $P < .001$) than in the general population ($r = -0.10$, 95% CI, −0.18 to −0.02; $t_{8.7} = -2.88$, $P = .019$).

3.2.5. Conduct problems

The meta-analysis of the association with conduct problems ($m = 46$, $k = 268$, $N = 19{,}356$) produced a significant effect size (r) of −0.14 (95% CI, −0.17 to −0.11; $t_{40.1} = -9.71$, $P < .001$) (Fig. 3), indicating that poorer executive function in childhood was associated with subsequent conduct problems.

Sample type emerged as a significant moderator, $F(2, 15.5) = 4.23$, $P = .034$. Specifically, executive function during childhood was more strongly associated with subsequent conduct problems in mixed-population ($r = -0.21$, 95% CI, −0.28 to −0.15; $t_{6.5} = -8.20$, $P < .001$) than in general-population studies ($r = -0.12$, 95% CI, −0.16 to −0.08; $t_{20.9} = -6.32$, $P < .001$).

3.2.6. Oppositional defiant disorder symptoms

The meta-analysis of the association with ODD symptoms ($m = 6$, $k = 65$, $N = 4684$) produced a significant effect size (r) of −0.10 (95% CI, −0.16 to −0.03; $t_{4.2} = -4.11$, $P = .013$) (Fig. 4), suggesting that poorer executive function during childhood was associated with more future ODD symptoms. There were not enough studies examining associations of executive function with ODD symptoms to conduct reliable moderator analyses.

3.2.7. Substance use

The meta-analysis of the association with substance use ($m = 24$, $k = 180$, $N = 15{,}231$) produced a significant combined effect size (r) of

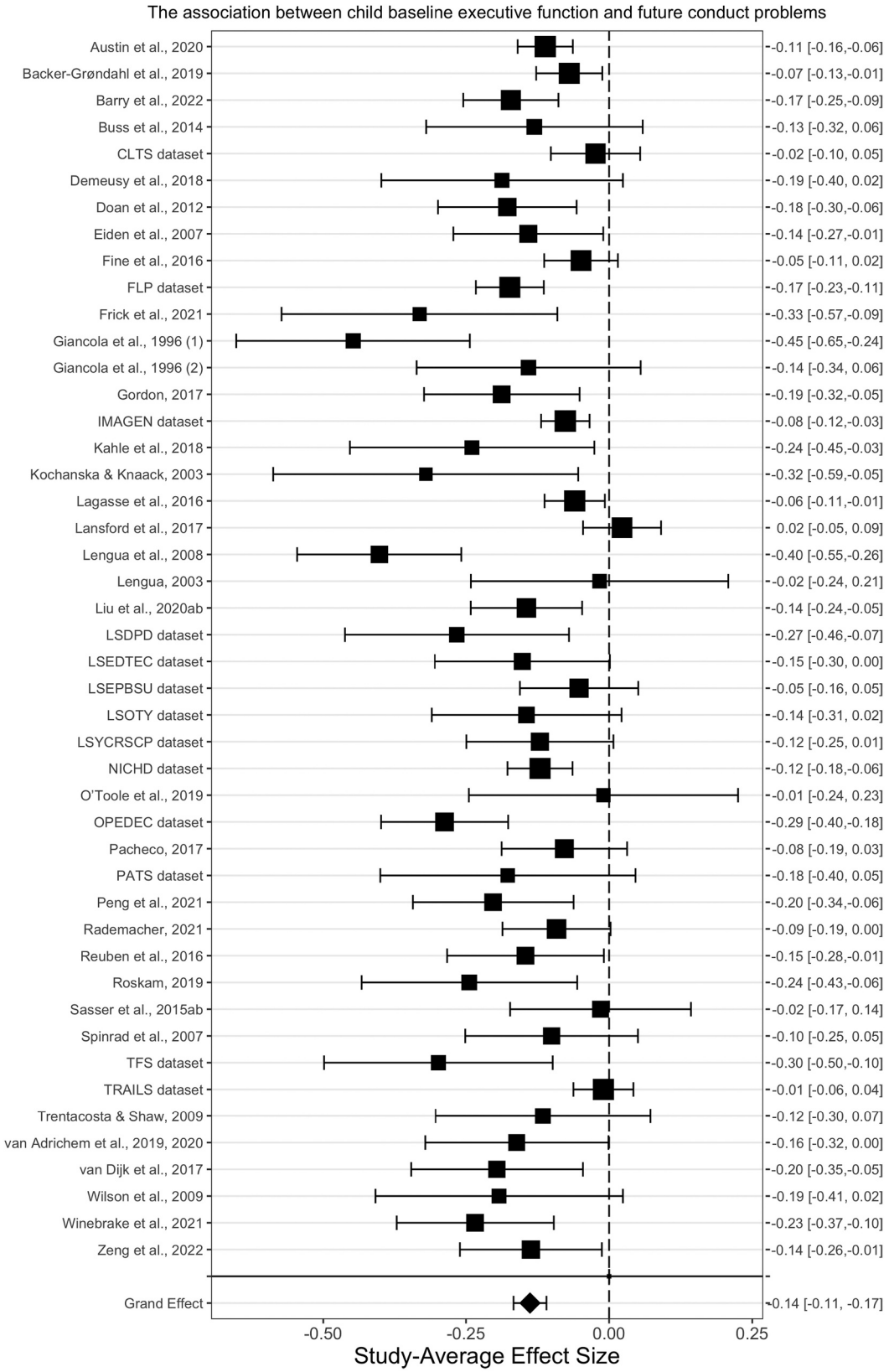

Fig. 3. Forest plot depicting study-average association between child baseline executive function and subsequent conduct problems.

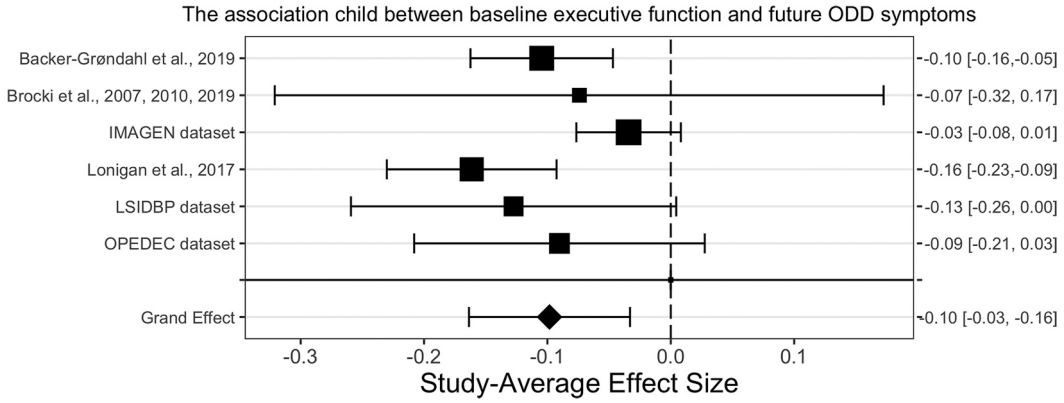

Fig. 4. Forest Plot Depicting Study-Average Association between Child Baseline Executive Function and Subsequent ODD symptoms.

−0.05 (95% CI, −0.07 to −0.03; $t_{17.7} = -5.15$, $P < .001$) (Fig. 5), indicating that poorer executive function during childhood was associated with greater future substance use.

The context of the executive function task emerged as a significant moderator, F (1, 11.6) = 8.74, $P = .012$. In particular, hot executive function task performance was more strongly associated with subsequent substance use ($r = -0.09$, 95% CI, −0.14 to −0.05; $t_{7.7} = -4.81$, $P = .001$), than was cool executive function task performance ($r = -0.03$, 95% CI, −0.05 to −0.01; $t_{12.7} = -3.01$, $P = .010$) (Fig. 6a).

3.2.8. *Broad externalizing problems*

The meta-analysis of the association with broad externalizing problems ($m = 21$, $k = 60$, $N = 26{,}184$) produced a significant combined effect size (r) of −0.11 (95% CI, −0.15 to −0.08; $t_{13.2} = -7.72$, $P < .001$) (Fig. 7), suggesting that poorer executive function during childhood was associated with greater levels of broad externalizing problems later in

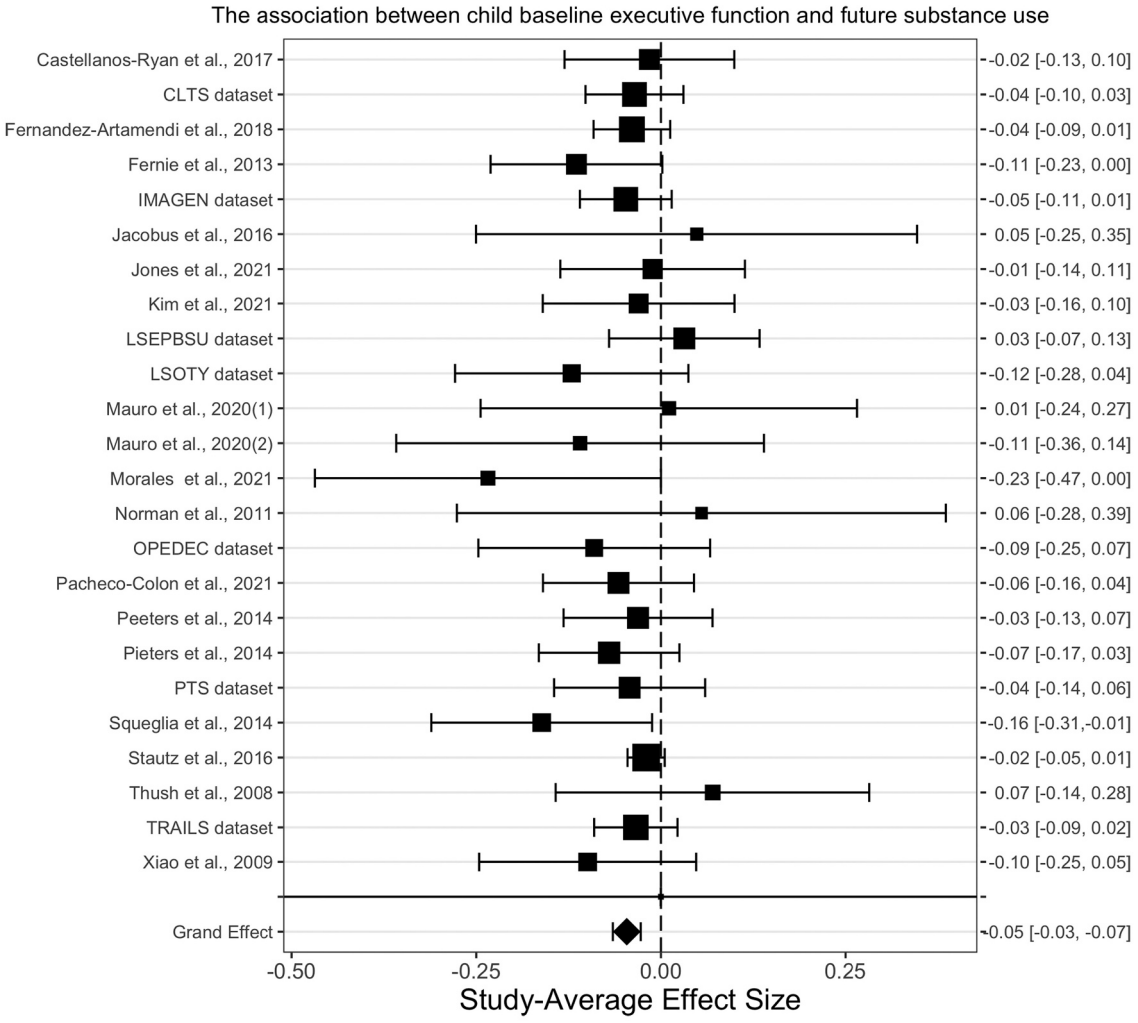

Fig. 5. Forest plot depicting study-average association between child baseline executive function and subsequent substance use.

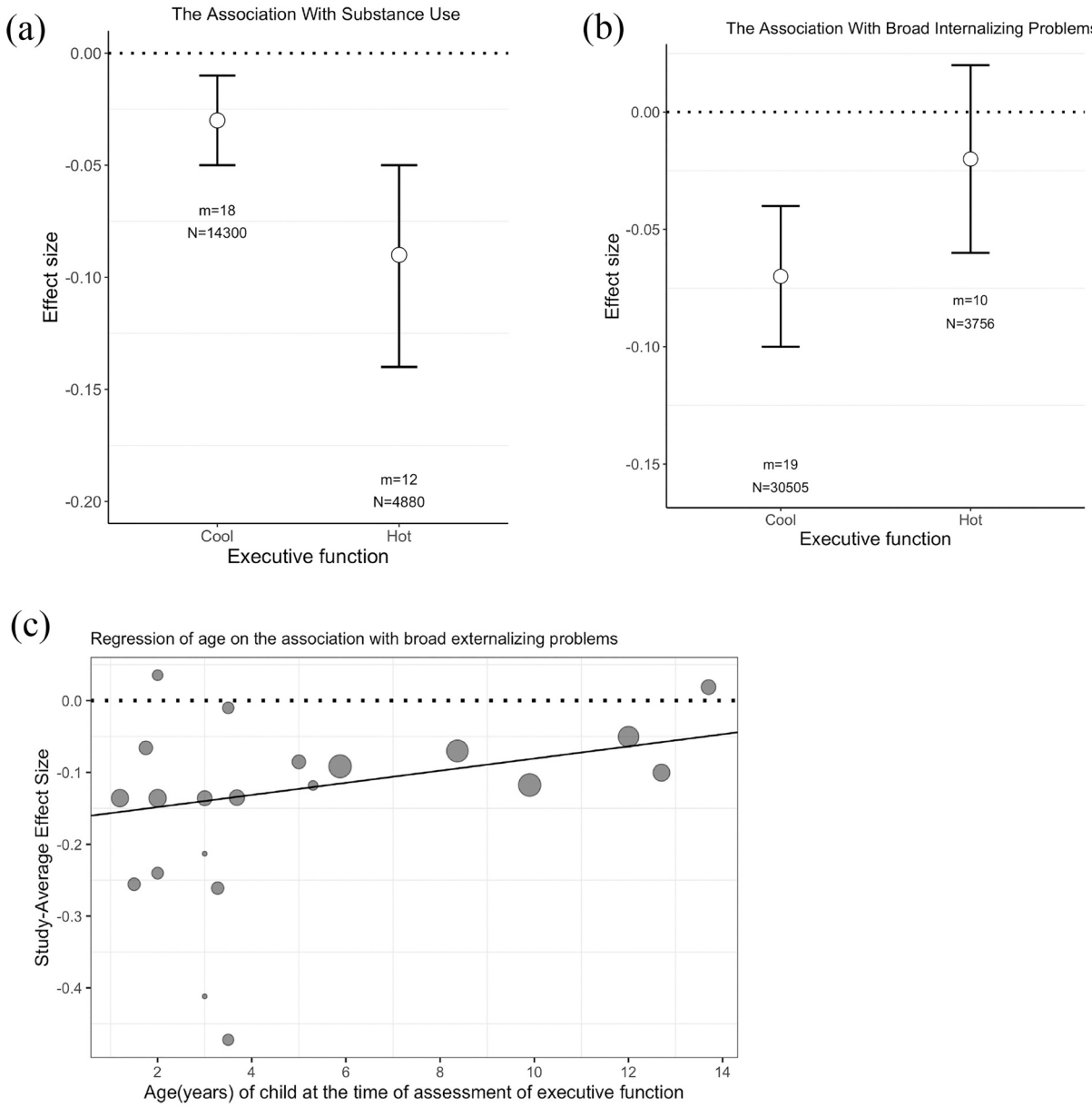

Fig. 6. Significant moderators of associations with substance use, broad externalizing problems, broad internalizing problems. Size of circles in the continuous plot indicates the relative weight given to that study in the analysis.

life.

Age at the time of executive function assessment emerged as a significant moderator of the association between baseline executive function and future broad externalizing problems, with the association becoming weaker (i.e., less negative) as age increased, $\beta = 0.01$, $t_{8.2} = 2.84$, $P = .021$ (Fig. 6c).

3.2.9. Depression symptoms

The meta-analysis of the association with depression symptoms ($m = 19$, $k = 88$, $N = 11{,}819$) produced a significant combined effect size (r) of −0.05 (95% CI, −0.08 to −0.03; $t_{15.6} = -4.07$, $P < .001$) (Fig. 8), indicating that poorer executive function during childhood was associated with more depression symptoms later in life.

3.2.10. Anxiety symptoms

The meta-analysis of the association with anxiety symptoms ($m = 12$, $k = 42$, $N = 6625$) produced a nonsignificant combined effect size (r) of −0.04 (95% CI, −0.11 to 0.03; $t_{10} = -1.22$, $P = .252$) (Fig. 9), which suggests that executive function during childhood was, surprisingly, not associated with subsequent anxiety symptoms.

3.2.11. Broad internalizing problems

This meta-analysis of associations with broad internalizing problems ($m = 28$, $k = 178$, $N = 32{,}383$) produced a significant combined effect size (r) of −0.07 (95% CI, −0.10 to −0.04; $t_{21.9} = -4.88$, $P < .001$) (Fig. 10), indicating that poorer executive function during childhood was associated with greater levels of broad internalizing problems later in life.

The context of the executive function task emerged as a significant moderator, F (1, 10.4) = 5.57, $P = .039$. In particular, cool executive function task performance was associated with greater levels broad internalizing problems later in life ($r = -0.07$, 95% CI, −0.10 to −0.04; $t_{13.4} = -4.96$, $P < .001$), whereas hot executive function task performance was not ($r = -0.02$, 95% CI, −0.06 to 0.03; $t_{7.0} = -0.84$, $P = .429$) (Fig. 6b).

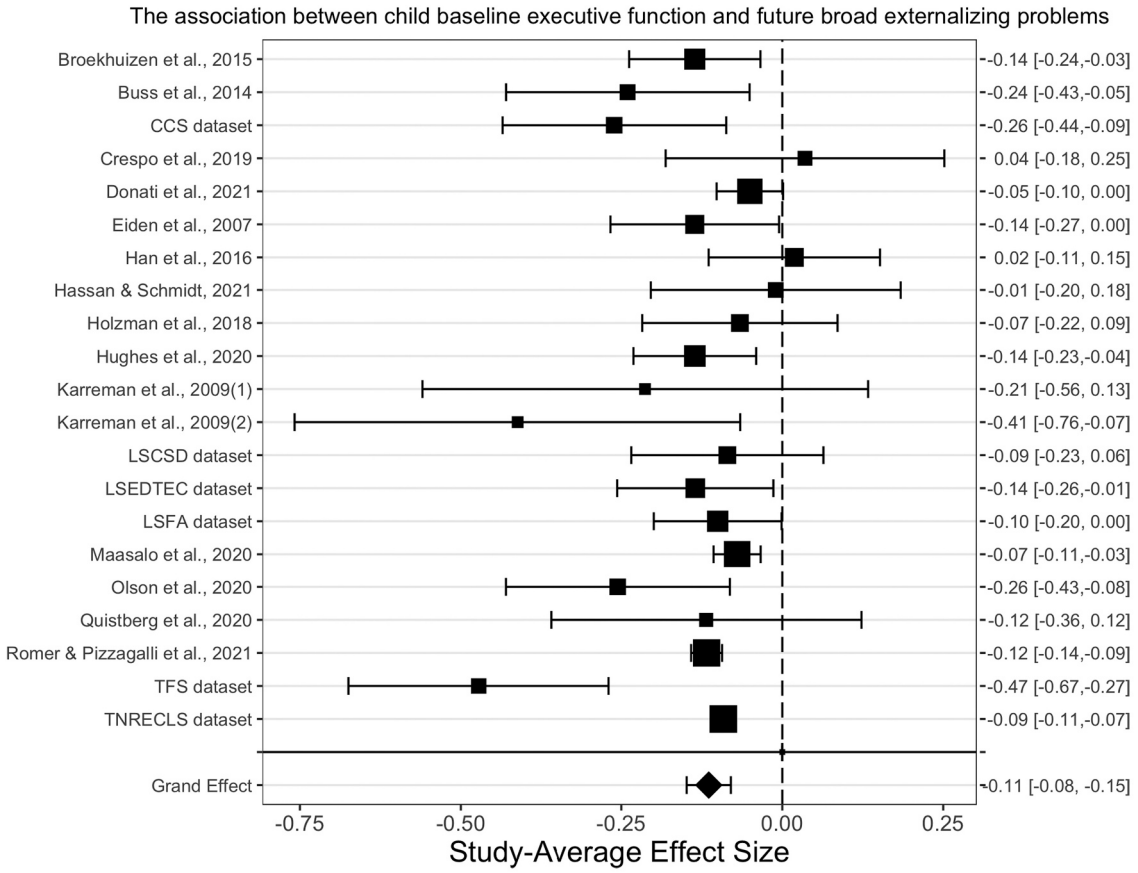

Fig. 7. Forest plot depicting study-average association between child baseline executive function and subsequent broad externalizing problems.

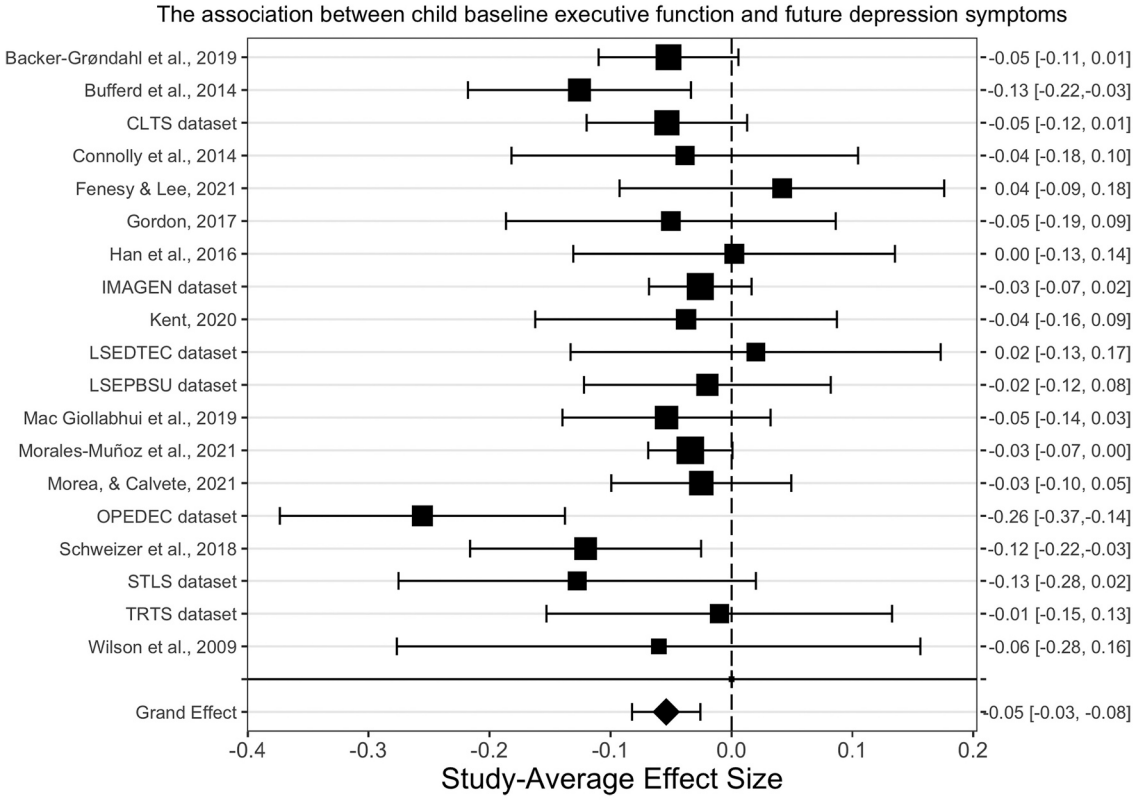

Fig. 8. Forest plot depicting study-average association between child baseline executive function and subsequent depression symptoms.

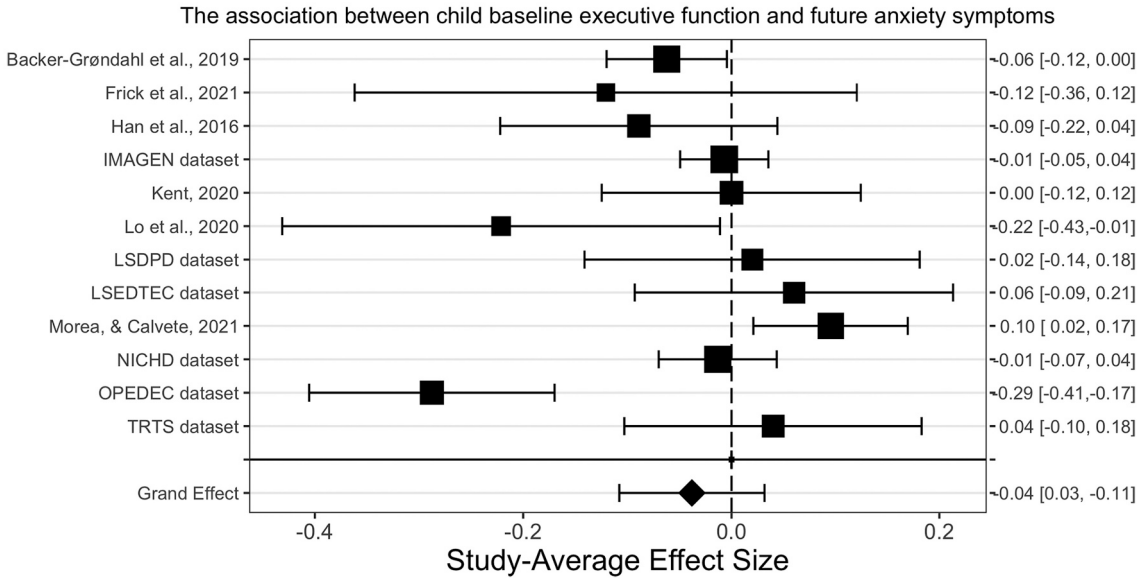

Fig. 9. Forest plot depicting study-average association between child baseline executive function and subsequent anxiety symptoms.

4. Discussion

Theoretical work has suggested that executive dysfunction may be a risk factor for later externalizing and internalizing problems (e.g., Eisenberg et al., 2010; Zelazo, 2020). To systematically evaluate and test this idea, we conducted the first systematic review and meta-analysis, to our knowledge, of longitudinal studies examining prospective associations between child executive functions and eight problem behaviors. We also examined several variables as potential moderators of these links. In general, this comprehensive review of 167 studies, including 1098 effect sizes and 66,119 participants, revealed that better executive function during childhood or adolescence was significantly associated with fewer subsequent ADHD symptoms, conduct problems, ODD symptoms, occurrences of substance use, broad externalizing problems, depression symptoms, and broad internalizing problems. Surprisingly, executive function during childhood or adolescence was not significantly associated with subsequent anxiety symptoms. The moderator analyses suggested that sample type moderated the associations of executive function with both ADHD symptoms and conduct problems, age moderated the association with broad externalizing problems, and the context of the executive function task (i.e., hot vs. cool) moderated the associations with both substance use and broad internalizing problems. Together, our results suggest that executive function during childhood or adolescence is prospectively and inversely related to many subsequent behavior problems, and executive dysfunction may thus be an important target for psychopathology prevention programs and interventions.

Research on executive functions in the context of psychopathology has generally found that executive dysfunction is present across disorders, potentially pointing to a transdiagnostic phenomenon (Beauchaine et al., 2017; Goschke, 2014; McTeague, Goodkind, & Etkin, 2016; Romer, Hariri, & Strauman, 2021; Snyder et al., 2019). For example, in reviewing meta-analyses, Snyder et al. (2015) found that executive function impairments were associated with many forms of psychopathology (e.g., ADHD, substance use) examined. Further, a recent systematic review and meta-analysis examined cognitive function (e.g., executive function) in relation to twelve major disorders/categories (Abramovitch et al., 2021). This meta-analysis found that all disorders reviewed were associated with lower cognitive performance, including poorer executive function, when compared with healthy controls. Our meta-analysis complements and extends those prior reviews and meta-analyses by examining longitudinal associations, finding that executive function during childhood or adolescence inversely related to most future externalizing and internalizing problems investigated (except anxiety symptoms) in both general (i.e., nonclinical) and clinical samples. Thus, our findings further support executive dysfunction as a transdiagnostic risk factor for psychopathology.

It should be noted that we observed relatively smaller effect sizes (e.g., $r = -0.19$ with ADHD symptoms, $r = -0.14$ with conduct problems) compared to those (e.g., $r = -0.26$) reported by previous clinical meta-analyses (e.g., Ogilvie, Stewart, Chan, & Shum, 2011; Wagner, Muller, Helmreich, Huss, & Tadic, 2015; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). This is not surprising, given the differences between previous work and the current study. For example, previous meta-analyses typically compared executive function performance between clinical and non-clinical samples, whereas our meta-analysis examined executive function in relation to problem behaviors across a variety of samples, including samples from typical, at-risk, mixed, and clinical populations. Additionally, we found that sample type moderated the associations between executive function and both ADHD symptoms and conduct problems. Childhood or adolescent executive function showed relatively weaker associations with ADHD symptoms and conduct problems in the general population than in mixed or at-risk populations, supporting the idea that sample differences may in part explain differences in effect size estimates obtained in our meta-analysis versus previous meta-analyses. Additionally, the current meta-analysis examined longitudinal associations, whereas previous meta-analyses focused on cross-sectional associations, and this difference may also have contributed to differences in effect size magnitude between meta-analyses.

4.1. ADHD symptoms

We found that, on average, higher levels of child baseline executive function was associated with less future ADHD symptoms. The symptoms of ADHD can be categorized into 2 types of behavioral problems: inattentiveness and hyperactivity/impulsiveness (American Psychiatric Association, 2013). Several theoretical models have been presented pointing to executive function such as inhibitory control and working memory as key predictors of symptom severity of ADHD (Barkley, 1997). Abnormalities in prefrontal cortical neural circuits that control these functions may be linked to the inability to strategically redirect attention or adapt behavior to contextual circumstances, which, in turn, may result in atypical development of self-regulation skills and an increase in behavioral symptoms of ADHD (Nigg, 2005).

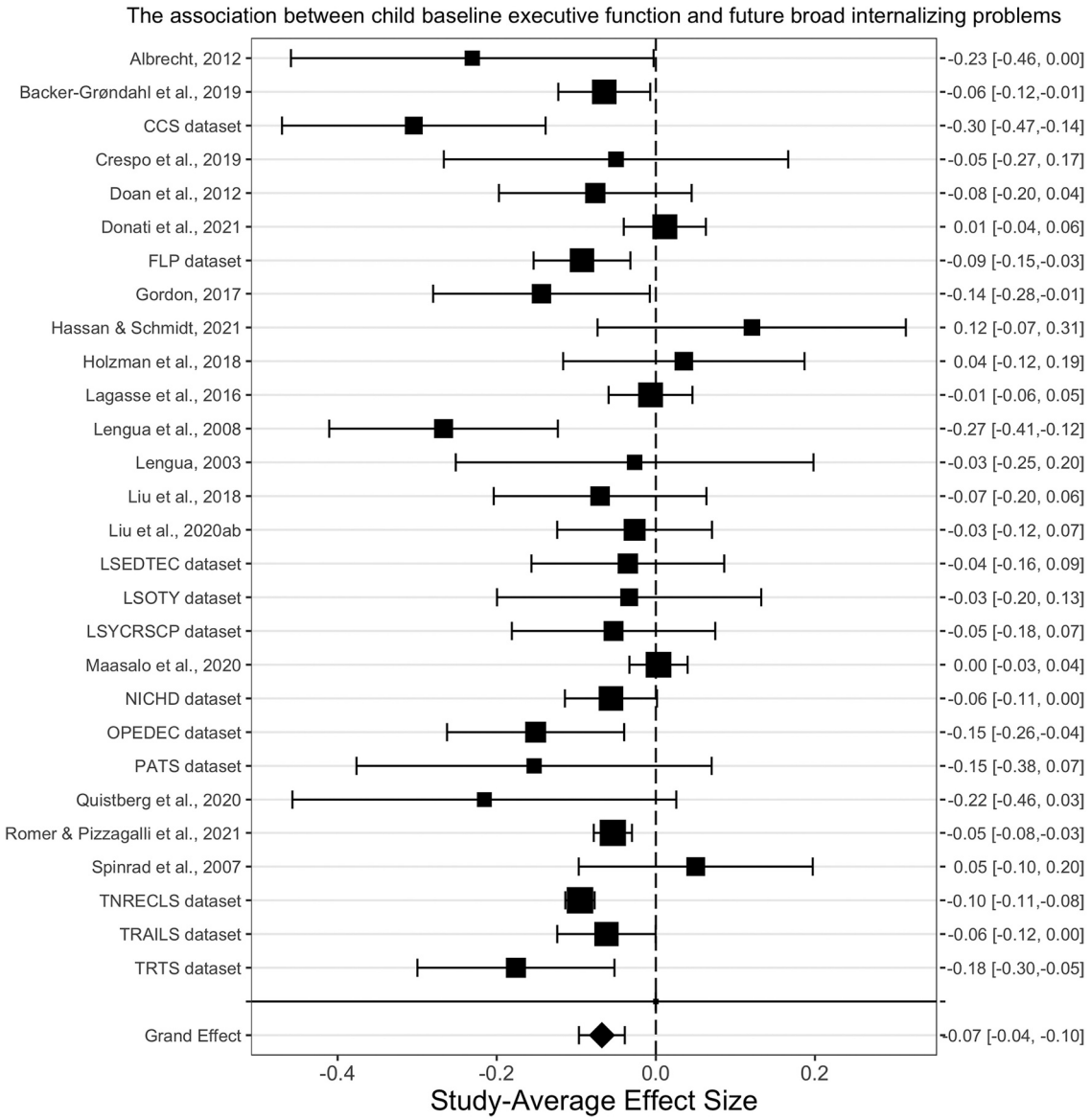

Fig. 10. Forest plot depicting study-average association between child baseline executive function and subsequent broad internalizing problem.

4.2. Conduct problems

We found a negative association between executive function during childhood or adolescence and subsequent conduct problems. Conduct problems represent a pattern of behavior characterized by violation of the rights of others and/or societal norms or authority figures, such as aggression, property destruction, and theft (American Psychiatric Association, 2013). Lower executive function might increase the risk of engaging in problem behaviors via a poorer ability to control emotions (e.g., anger) when facing psychosocial stressors, decreased behavioral inhibition, and poorer regulation of socially appropriate behavior in challenging contexts (Sprague, Verona, Kalkhoff, & Kilmer, 2011).

4.3. Oppositional defiant disorder symptoms

We found an overall significant association between child baseline executive function and subsequent ODD symptoms. ODD symptoms include a pattern of angry/irritable mood, argumentative/defiant behavior, or vindictiveness (American Psychiatric Association, 2013). ODD symptoms and conduct problems are both related to behavior problems that bring the individual in conflict with authority figures (e.g., teachers) (American Psychiatric Association, 2013). Not surprisingly, the magnitude of the association between executive function and ODD symptoms is similar to the association between executive function and conduct problems. However, because of the small study set sizes, we were unable to examine any possible moderators of this association. Therefore, future research should examine this association further.

4.4. Substance use

We also found a small association with childhood or adolescent executive dysfunction and later substance use, with the context of the executive function task moderating this relationship. Poor executive function may be both a consequence and a cause of substance use (Bickel et al., 2018). Long-term drug use appears to harm the frontal-striatal system, which could impair executive function (Klugah-Brown et al., 2020). On the other hand, several systematic reviews have suggested that poorer executive function can increase risk for substance use (Castellanos-Ryan & Conrod, 2020; Verdejo-Garcia & Albein-Urios, 2021). For example, poor inhibitory control (one of the components of executive function) could make it difficult for individuals to resist the urge for a reward (e.g., cannabis), or to refrain from risky behavior while

intoxicated. Supporting this vulnerability marker proposal, our meta-analysis showed childhood or adolescent executive function prospectively predicted future substance use.

It should be noted that the association of executive function with substance use was small, which could be driven by the included studies using mostly cool executive function tasks. In support of this, we found that the context of the executive function task moderated the association between executive function and substance use. Specifically, the prospective association between executive dysfunction and substance use was significantly stronger when the executive function task was a "hot" executive function task than when it was a "cool" task. Therefore, poorer hot executive function task performance in childhood or adolescence may be an important risk factor for later development of substance use. The results here corroborate the notion of a recent systematic review, which also found that executive function processes involved in reward-related valuation were consistent predictors of substance use vulnerability (Verdejo-Garcia & Albein-Urios, 2021). Future studies aimed at reducing substance use symptoms via modifying executive functions may thus benefit most from modifying hot executive function task performance.

4.5. Broad externalizing symptoms

Executive dysfunction during childhood also showed a significant prospective association with broad externalizing problems, which includes ADHD symptoms, conduct problems, and ODD symptoms. Together with findings of the previous meta-analysis of cross-sectional studies (Schoemaker et al., 2013), the associations of executive function with externalizing problems appear quite robust. We found that age at executive function assessment moderated the association between executive function and broad externalizing problems: In general, as age increased, the prospective association between executive function and later externalizing problems became weaker. Although some have suggested that early childhood executive function may be a relatively poor predictor of externalizing symptoms because executive function is not well developed in early childhood (Frick, Forslund, & Brocki, 2019; Pauli-Pott & Becker, 2011; Schoemaker et al., 2013), this argument was not supported by our analysis. We found that poorer executive function was more strongly related to subsequent externalizing problems when children were younger rather than older. Why the association decreased in magnitude in older-age studies is not entirely clear, but it could be that the decreasing prevalence of externalizing problems from childhood to adolescence (Costello, Copeland, & Angold, 2011; Roskam, 2019) makes the influence of executive function skills less evident. Finally, it should be noted that we did not observe the moderating effect of age on the associations of executive function with either ADHD symptoms or conduct problems. This differential moderation between broad externalizing problems and ADHD symptoms or conduct problems might be explained by sample type differences: Most studies examining associations of executive function with ADHD symptoms or conduct problems used general, at-risk, mixed or clinical samples, whereas most studies examined the associations with broad externalizing problems in general samples. Sample type and age might interactively moderate associations of executive function with externalizing behaviors, perhaps making the moderating role of age less evident in associations with ADHD symptoms or conduct problems in our study set.

4.6. Depression symptoms

Our meta-analysis revealed that better executive function during childhood or adolescence was also prospectively associated with fewer depression symptoms. Associations between executive function and depression may occur for three reasons (Friedman et al., 2018). First, executive dysfunction may cause or exacerbate depressive symptoms. Second, depression may also directly or indirectly impair executive function. Third, executive function deficits may be associated with depression because of a shared cause (e.g., stress). The longitudinal association of executive function and depression symptoms observed in this review suggests that executive function may be implicated in the etiology of depression, though the influence of executive function might be small. However, readers should be cautious when interpreting the current results, since the prospective association observed here is still correlational, not causal. More longitudinal studies are still needed to explore whether earlier child executive function deficits could predict the onset of depression, especially in community samples of individuals who have never experienced depression.

4.7. Anxiety symptoms

We did not observe a significant prospective association between executive function during childhood or adolescence and anxiety symptoms. This was unexpected, as previous meta-analyses found executive function differences between anxious and non-anxious individuals (Shi, Sharpe, & Abbott, 2019). In addition, another meta-analysis found that anxiety is associated with an increased risk of cognitive impairment in elderly community samples (Gulpers et al., 2016). Although comparing across meta-analyses is difficult given study set differences, it is tempting to speculate that clinical or subclinical anxiety symptoms may have deleterious effects on executive function performance, while executive function deficits may not precede the development of anxiety.

4.8. Broad internalizing symptoms

Poor executive function during childhood or adolescence showed a significant prospective association with broad internalizing problems—which includes depression symptoms, anxiety symptoms, or more broad measures of internalizing symptoms, such as loneliness. Theoretically, executive dysfunction may be a risk factor for the development of internalizing behaviors due to the role of executive function in emotion regulation (e.g., Eisenberg et al., 2010). It should be noted, however, that the significant association with broad internalizing symptoms was small. Nonetheless, small effect sizes can have meaningful practical and clinical consequences at the population level (Funder and Ozer, 2019), and this is especially true in this case, given that executive function can be intervened on (Diamond, 2013). An interesting finding in these analyses is that the context of the executive function task emerged as a moderator, with cool executive function task performance being a stronger predictor of broad internalizing problems than hot executive function task performance—which was opposite of the moderating direction seen in relation to substance abuse. This result implies that the context of executive function (i.e., whether it is recruited within a hot or cool context) may be important for associations with internalizing problems or substance use, highlighting the importance of considering this factor in future work.

4.9. Executive function as a transdiagnostic risk factor for multiple forms of behavior problems through common mechanisms

In the above section, we discussed the possibilities that poor executive function confers risk for multiple forms of behavior problems via different mediating mechanisms (e.g., emotion regulation, behavior regulation, attention control) specific to the type of behavior problem. In addition, it also possible that poor executive function might confer risk for multiple forms of psychopathology more broadly through some common mechanism(s), such as the *p* factor. Recent conceptual models have proposed that executive dysfunction is a risk factor for general psychopathology (often referred to as the "*p* factor") (Beauchaine & Zisner, 2017; Hankin et al., 2016; Romer, Hariri, & Strauman, 2021; Snyder et al., 2019). The *p* factor reflects a shared vulnerability to experience an array of psychopathology symptoms across diagnostic categories (Caspi et al., 2014). In support of the idea that executive dysfunction may confer a general risk for psychopathology, recent

studies have found that poorer executive function is associated with higher levels of the *p* factor in children and adolescents (Bloemen et al., 2018; Cardenas-Iniguez et al., 2022; Castellanos-Ryan et al., 2016; White et al., 2017). Moreover, recent neuroimaging and genetics research also supports this idea. Specifically, structural and functional neural abnormalities in brain areas related to executive function (e.g., frontoparietal, visual association circuits) have been identified in studies as neural correlates of the *p* factor (Romer et al., 2021; Romer & Pizzagalli, 2022; Snyder, Hankin, Sandman, Head, & Davis, 2017). Similarly, shared genetic markers for both executive dysfunction and general psychopathology symptoms have been identified (Freis et al., 2022; Harden et al., 2020; Hatoum, Rhee, Corley, Hewitt, & Friedman, 2018). For example, Harden et al. (2020) found that genetic markers of executive dysfunction were robustly correlated with genetic markers of the *p* factor. To sum up, although particular deficits in specific skills dependent upon executive functions (e.g., emotion regulation) might confer risk for one form of psychopathology over another, executive dysfunction might confer a transdiagnostic risk for psychopathology and multiple forms of behavior problems.

4.10. Strengths, limitations, and future directions

The main strengths of this meta-analysis include its focus on prospective associations of executive function with externalizing and internalizing problems, examination of many different problem behaviors, examination of several potential important moderating factors, and our analysis of a large number of studies. However, several limitations should also be noted. First and foremost, although we focused on prospective associations, our results are still correlational, not causal. Additional longitudinal research with executive function and behavior problems assessed at multiple time points is needed to determine if executive dysfunction is a risk factor for or consequence of behavior problems, or if it is both. In addition, repeated assessment of behavior problems over time might clarify the role of changes in executive function in the development or remission of psychopathology. Some models of mental health disorders have proposed that improving executive functions may help to reduce symptoms of psychopathology (e.g., Halperin & Schulz, 2006), and this idea has been supported by several recent studies (e.g., Karalunas et al., 2017; Rajendran et al., 2013). Because the current meta-analysis only focused on a static, correlational (albeit longitudinal) picture of executive functions in relation to behavior problems, when more studies have examined both executive functions and psychopathology at two or more timepoints, an additional meta-analysis or systematic review of the association between changes in both constructs will be warranted. Second, only twenty independent samples reported the correlations of any of the eight types of behavior problems with executive function while adjusting for baseline behavior problems. Because of this, we were not able to investigate whether covarying baseline behavior problems moderated any of the analyses that we conducted. After more studies examine the prospective associations of executive function with behavior problems controlling for baseline behavior problems, an additional meta-analysis of these adjusted associations will be warranted—especially because this might provide stronger examination of the longitudinal role of executive function in these behaviors. Third, the current meta-analysis was unable to differentiate between common and specific executive functions in associations with problem behaviors, as the moderator analyses were not significant. Similar to previous meta-analyses (e.g., Shields et al., 2016; Yang et al., 2018), we coded task outcomes thought to assess executive function into several core executive functions based upon previous empirical or theoretical literature. However, the unity/diversity model proposes that performance on all executive function task outcomes depend in part on a common executive function factor, with some outcomes also indexing specific executive functions (e.g., updating and shifting specific) (Friedman & Miyake, 2017), and this model has been supported by recent studies (e.g., Brydges, Fox, Reid, & Anderson, 2014). Therefore, it is unclear whether the associations observed in current meta-analysis reflect associations with a common executive function, specific executive functions, or both, and the observed associations may be attenuated if associations are specific to any one or more of the executive function components. Fourth, the number of studies that followed participants into adulthood was relatively small (e.g., eleven in total), as were very long-term follow-up studies (e.g., ten years). Therefore, our ability to detect long-term prospective associations of child baseline executive function with behavior problems, especially in adults, was limited. More studies are needed to examine whether child baseline executive function could predict mental health outcomes in adulthood. Fifth, there are many subtypes of substance use (e.g., alcohol, tobacco, illicit drugs). However, there were not enough studies in each of these subtypes to permit separate meta-analyses on each of them. Sixth, the current meta-analysis did not include studies that used questionnaire assessments of executive function such as Behavior Rating Inventory of Executive Function (BRIEF) (Baron, 2000) or Child Behavior Questionnaire (Rothbart, Ahadi, Hershey, & Fisher, 2001). We made the decision to exclude questionnaire assessments of executive function because of two reasons: First, the current work was based on executive function theories (Diamond, 2013; Miyake & Friedman, 2012; Zelazo, 2020) that were developed from performance-based tasks, not questionnaires; second, the correlations of direct assessment and questionnaires of executive function are very low, suggesting that they are measuring different constructs (Snyder, Friedman, & Hankin, 2021). However, given that numerous studies have explored the associations of questionnaire-measured executive function and behavior problems, a future meta-analysis of these studies might also be informative. Seventh, the associations with internalizing problems in the current meta-analysis were mainly observed in general samples, and these associations need to be further examined in high-risk or clinical populations. Finally, because of the relatively small number of studies examining ODD symptoms, future studies should continue to explore its association with executive function.

4.11. Clinical implications

The results of this meta-analysis have implications for identification of early markers of and intervention targets for externalizing and internalizing behaviors. We found that executive function during childhood or adolescence was inversely associated with many subsequent behavior problems, suggesting that researchers should consider incorporating executive function into their clinical prediction models and early intervention programs. More specifically, extending on past studies based on other important factors (e.g., temperament) (e.g., Goh, Lee, Martel, Karalunas, & Nigg, 2020; Karalunas, Gustafsson, Fair, Musser, & Nigg, 2019), the results of the current meta-analysis suggest that integrating executive function into risk-factor models of behavior problems may improve early identification of children who are at risk of developing psychopathology. In addition, numerous studies have found evidence that executive function can be trained and improved in both preschool-age and school-age children (Diamond & Lee, 2011). However, the far transfer effects of executive function training remain unclear (e.g., Melby-Lervag, Redick, & Hulme, 2016). Therefore, future randomized controlled trials focused on far transfer and long-term effects are needed to examine whether early executive function training in children can mitigate clinical symptoms, such as externalizing and internalizing problems. In short, the transdiagnostic risk of executive dysfunction suggests that targeting executive dysfunction may facilitate early identification of and interventions to improve behavior problems.

5. Conclusions

Executive functions play a critical role in everyday life. In a meta-analysis of 167 studies, we found that executive function during childhood was inversely associated with many subsequent externalizing and

internalizing problems, including ADHD symptoms, conduct problems, ODD symptoms, substance use, broad externalizing problems, depression symptoms, and broad internalizing problems. Moreover, we found that sample type moderated associations of executive function with both ADHD symptoms and conduct problems, age moderated the association with broad externalizing problems, and the context of the executive function task moderated associations with both substance use and broad internalizing problems. Although correlational, our results justify the design of subsequent studies that include executive function as a potential target for earlier identification of and interventions aiming to improve behavior problems.

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CRediT authorship contribution statement

Yingkai Yang: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft. **Grant S. Shields:** Formal analysis, Methodology, Software, Supervision, Visualization, Writing – review & editing. **Yaoyao Zhang:** Data curation. **Huimin Wu:** Data curation. **Hong Chen:** Conceptualization, Validation. **Adrienne L. Romer:** Supervision, Writing – review & editing.

Declaration of Competing Interest

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cpr.2022.102194.

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