Executive Functioning and Emotion Regulation in Children with and without ADHD

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Abstract

Difficulties with emotion regulation affect the majority of youth with attention-deficit/hyperactivity disorder (ADHD) and predict greater functional impairment than ADHD symptoms alone. Deficits in executive functioning are also present for most children with ADHD, and have been linked with emotion regulation difficulties in both clinical and neurotypical populations throughout development. The current study was the first to assess all three core executive functions (working memory, inhibitory control, set shifting) simultaneously in a clinically-diverse sample of children with and without ADHD and common comorbidities and investigate the extent to which they uniquely predict emotion dysregulation. A sample of 151 children ages 8-13 years (M=10.36, SD=1.52; 52 girls; 70.2% White/Non-Hispanic) were assessed using a criterion battery of executive functioning tasks, teacher-reported ADHD symptoms, and parent-reported emotion regulation. Results of the bias-corrected, bootstrapped conditional effects path model revealed that better-developed working memory predicted better emotion regulation (β=0.23) and fewer ADHD symptoms (β=−0.21 to −0.37), that ADHD symptoms (β=−0.18 to −0.20) independently predicted emotion dysregulation, and that working memory exerted indirect effects on emotion regulation through both inattention and hyperactivity/impulsivity (β=0.04-0.07). Sensitivity analyses indicated that these effects were generally robust to control for age, sex,

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Conflict of Interest
The authors have no conflicts of interest to report.

Ethical Approval
All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent
Informed consent was obtained from all individual participants included in the study.

executive function interrelations, and inclusion/exclusion of children with co-occurring ASD. These findings underscore the importance of working memory (relative to inhibitory control and set shifting) and its relations with ADHD symptoms for understanding children's emotion regulation skills, and may help explain the limited efficacy of first-line ADHD treatments, which do not target working memory, for improving emotion regulation skills.

Keywords

Executive function; Emotion regulation; Working memory; ADHD

Introduction

Attention-deficit/hyperactivity disorder (ADHD) is a neurodevelopmental disorder characterized by impairing symptoms of inattention, hyperactivity, and impulsivity (American Psychiatric Association, 2013). ADHD affects approximately 5% of school-aged children (Polanczyk et al., 2014), and a majority of children with ADHD experience deficits in at least one domain of emotional functioning, including emotion recognition, emotional lability, and/or emotion regulation (Graziano & Garcia, 2016). Understanding the mechanisms and processes that underlie emotion dysregulation in ADHD is imperative given that co-occurring emotion dysregulation is associated with increased functional impairment (e.g., Classi et al., 2012) and is resistant to first-line ADHD treatments, including medication and behavioral therapy (Galanter et al., 2003; Waxmonsky et al., 2008). Executive functioning represents a promising target for investigation, given (a) experimental evidence linking these higher-order cognitive functions with one's skill at regulating emotions in neurotypical samples (e.g., Schmeichel & Tang, 2015; Wante et al., 2017); and (b) the high prevalence of executive dysfunction in children with ADHD (e.g., Alderson et al., 2007; Kasper et al., 2012; Kofler et al., 2019). Previous research with ADHD samples suggests cross-sectional (Groves et al., 2020; Sjowall et al., 2013) and potentially functional relations between specific executive functions and emotion regulation (Tarle et al., 2021). To our knowledge, however, no study to date has concurrently investigated all three of the primary executive functions (working memory, inhibitory control, set shifting; Miyake et al., 2000) to characterize the extent to which each executive function uniquely predicts ADHD-related emotion dysregulation. The present study investigates the relations among each executive function, ADHD symptoms, and emotion regulation using a multi-method, multi-informant approach in a clinically diverse sample.

ADHD and Emotion Regulation

Emotion regulation is a complex process involving one's physiological, experiential, and behavioral expressions of an emotion and the ability to modulate the speed and intensity of escalation and de-escalation of that emotion (Bunford et al., 2015; Zelkowitz & Cole, 2016). Approximately 48%-54% of pediatric ADHD cases exhibit impairments in emotion regulation based on converting meta-analytic effect sizes (d = 0.80-0.95; Graziano & Garcia, 2016) into the proportion of population overlap (Zakzanis, 2001). Understanding and mitigating emotion dysregulation in ADHD is imperative given that it increases the burden of illness associated with ADHD, including predicting greater academic and social impairment (Bunford et al., 2018; Classi et al., 2012; Qian et al., 2016), higher rates of health care utilization (Classi et al., 2012), and higher daily parenting stress (Walerius et al., 2016) than ADHD symptoms alone (Bunford et al., 2014). Additionally, emotion dysregulation persists into adulthood for many people with ADHD (Richard-Lepouriel et al., 2016), and it portends increased risk for the development of comorbid psychopathology (e.g., oppositional defiant disorder, anxiety, depression; Steinberg & Drabick, 2015). Despite the significant impairment associated with emotion regulation difficulties for children with ADHD, current first line treatments for ADHD - including psychostimulants (Galanter et al., 2003) and behavioral parent training (Waxmonsky et al., 2008) - often do not reduce emotion dysregulation. Investigating the correlates of, and possible etiological contributions to, emotion regulation difficulties in ADHD is an essential step in eventually developing/ modifying appropriately targeted treatments to reduce the distress and impairment that emotion dysregulation presents for individuals with ADHD.

ADHD and Executive Functioning

Many theories posit that ADHD is, in essence, a disorder of executive dysfunction (for review, see Kofler et al., 2016), but heterogeneity in the disorder is increasingly acknowledged. Specifically, there is heterogeneity in etiological pathways to ADHD (Hinshaw, 2018; Luo et al., 2019), as well as variability in the presence of executive dysfunction among individuals with ADHD (Kofler et al., 2018; Nigg et al., 2005). For example, working memory is impaired in 30% to 85% (Coghill et al. 2014; Fair et al. 2012; Fosco et al., 2019; Kofler et al., 2018; Karalunas et al., 2017), inhibitory control is impaired in 21% to 46% (Coghill et al., 2014; Kofler et al., 2018; Nigg et al., 2005; Solanto et al., 2001; Sonuga-Barke et al., 2010), and set shifting is impaired in 30% to 38% of children with ADHD (Kofler et al., 2018; Willcutt et al., 2005). Additionally, a subset of children with ADHD do not appear to be significantly impaired in any executive functioning domain, with estimates for this non-impaired subset ranging from 11% to 79% (Biederman et al., 2004; Coghill et al., 2014; Fair et al., 2012; Geurts et al., 2006; Kofler et al., 2018; Nigg et al., 2005; Solanto et al., 2001; Sonuga-Barke et al., 2010).

Although estimates of the proportion of children with ADHD who exhibit executive dysfunction vary widely, this variability may be attributable to limitations in the measurement of executive functions within the clinical literature rather than a flaw in the conceptual link between executive dysfunction and ADHD (Snyder et al., 2015; Sonuga-Barke et al., 2008). Indeed, when considering only studies that used criterion executive function tests informed by the cognitive literature such as those used in the current study (for review, see Snyder et al., 2015), estimates of the proportion of children with ADHD with intact executive functioning in all domains are relatively small, ranging from 10-15% (Karalunas et al., 2017; Kofler et al., 2018). Further, executive functioning predicts a range of functional impairments associated with ADHD (Efron et al., 2020; Kofler et al., 2011; Miller & Hinshaw, 2010), pointing to the utility of continued investigation about the role of executive dysfunction in ADHD. Given the evidence that ADHD is associated with large magnitude deficits in both emotion regulation and executive functioning, examining the manner in which these deficits relate to each other is imperative to appropriately characterizing ADHD and its associated difficulties.

Executive Functioning and Emotion Regulation

Among the diverse models of executive functioning that have been hypothesized, the present study defines executive functions as a set of three interrelated cognitive processes (working memory, inhibitory control, and set shifting). This framework has been supported extensively via theoretical and factor-analytic work in both adults (Miyake et al., 2000) and children (Karr et al., 2018). Executive functions support problem-solving, planning, and goal-directed behaviors (Kofler et al., 2019), including the regulation of emotion (Zelazo & Cunningham, 2007). In neurotypical populations, executive functions predict emotional reactivity and expressiveness (Schmeichel et al., 2008) as well as the use of effective emotion regulation strategies (Lantrip et al., 2015; Rutherford et al., 2015). The association between executive functioning and emotion regulation holds across development, such that the constructs are related beginning in early childhood (Binder et al., 2020; Wolfe & Belle, 2007) and throughout the lifespan into late adulthood (Charles & Carstensen, 2007; Sperduti et al., 2017).

Interestingly, although the literature generally demonstrates strong links between executive functions and emotional functioning (Schmeichel & Tang, 2015; Wante et al., 2017), findings regarding the role of specific executive functions and emotion regulation are more variable. For example, most studies investigating working memory find that better developed working memory predicts more effective emotion regulation (McRae et al., 2012; Opitz et al., 2014; Rutherford et al., 2016; Schweizer et al., 2011; Schweizer et al., 2013; Schweizer et al., 2017), though a smaller proportion of extant literature does not replicate this relation (Dubert et al., 2016; Gyurak et al., 2009; Gyurak et al., 2012; Marceau et al., 2018). Similarly, inhibitory control has been linked with emotion regulation repeatedly (Carlson et al., 2007; Falquez et al., 2015; Feng et al., 2008; Ferrier et al., 2014; Hendricks & Buchanan, 2016; Hoeskma et al., 2004; Leen-Feldner et al., 2004), but not universally (Gyurak et al., 2012). Finally, set shifting is often (De Lissnyder et al., 2010; Gul & Khan, 2014; Hughes et al., 1998; Johnson, 2009; Martins et al., 2016; Moreira et al., 2019; Murphy et al., 2012), but not always (Aker et al., 2014; Fuster et al., 2009), related to emotion regulation skills.

ADHD, Executive Functions, and Emotion Regulation

A similar pattern emerges for children with ADHD, with recent studies linking working memory (Groves et al., 2020; Tarle et al., 2021), inhibitory control (Sjowall et al., 2013; Tenenbaum et al., 2019), and set shifting (Sjowall et al., 2013) with the disorder's well-documented emotion regulation difficulties. Critically, however, most studies examining these relations have investigated executive function(s) in isolation rather than determining whether specific executive functions uniquely predict emotion dysregulation. A partial exception to this critique is a recent study by Sjowall and colleagues (2013), who reported that their ADHD group exhibited worse executive functioning and emotion regulation relative to controls, and found that all three executive functions were significantly correlated with emotion regulation. Despite the notable strengths of this study, however, it is not clear to what extent the relations among each executive function and emotion regulation reflect shared variance across the interrelated executive functions versus significant contributions of particular executive processes or the degree to which ADHD symptoms account for shared variance in executive dysfunction and emotion dysregulation.

Current Study

Taken together, research indicates that emotion dysregulation is present in most children with ADHD (Graziano & Garcia, 2016), portends risk for poorer outcomes than ADHD alone (Classi et al., 2012; Qian et al., 2016; Walerius et al., 2016), and is not ameliorated by current first-line treatments for ADHD (Galanter et al., 2003; Waxmonsky et al., 2008). Additionally, ADHD is associated with impairments in working memory, inhibitory control, and potentially set shifting (Willcutt et al., 2005; Irwin et al., 2019). Further, working memory, inhibitory control, and set shifting have all been associated with emotion regulation skills (e.g., Choi, 2012; Schmeichel et al., 2008; Tenenbaum et al., 2019), including in pediatric ADHD samples (e.g., Sjowall et al., 2013). The current study builds on this evidence base and is the first to investigate the unique contributions of each executive function to children's emotion regulation skills using a multi-method, multi-informant approach in a clinically diverse sample of children with and without ADHD. Additionally, this study serves as an extension of our previous work that included a subset of the current sample (Groves et al., 2020), in which we found that working memory deficits predicted emotion dysregulation difficulties both directly and indirectly via ADHD hyperactive/impulsive symptoms. The present study improves on this work by explicitly accounting for the other highly interrelated executive functions, using tasks that assess all three of the 'working' functions of working memory (i.e., reordering, updating, and dual processing rather than just reordering as in our previous work; Fosco et al., 2020), and using a measure that assesses emotion regulation more comprehensively than the broadband screening questionnaire subscale used in our earlier study. Based on our previous work and the available literature reviewed above, we hypothesized that all three executive functions would predict emotion regulation, and that these relations would be at least partially attributable to the shared variance among executive functions and ADHD symptoms, that, in turn, also predict emotion regulation (i.e., we predicted both direct and indirect effects of working memory, inhibitory control, and set shifting on emotion regulation). We examined inattention and hyperactivity/impulsivity separately based on evidence that these symptom clusters differentially impact other ADHD-related impairments (Kuntsi et al., 2014), but we did not have specific hypotheses for these symptom clusters due to mixed findings in extant literature.

Method

Participants

The sample comprised 151 children aged 8 to 13 years (*M*=10.36, *SD*=1.52; 52 girls) from the Southeastern United States, recruited by or referred to a university-based children's learning clinic (CLC) through community resources (e.g., pediatricians, community mental health clinics, school system personnel, community recruitment events, website/Internet postings, self-referral) from 2016 to 2019. All parents and children gave informed consent/assent, and the Florida State University Institutional Review Board approved the study.

Sample race and ethnicity was mixed with 106 White/Non-Hispanic (70.2%), 18 Black (11.9%), 13 Hispanic/Latino (8.6%), 13 multiracial (8.6%) children, and 1 Asian (0.7%) child. All children spoke English.

All children and caregivers completed a comprehensive evaluation that included detailed, semi-structured clinical interviewing and multiple norm-referenced parent and teacher questionnaires. A detailed account of the comprehensive psychoeducational evaluation can be found in the larger study's preregistration: https://osf.io/nvfer/. The final sample included 33 children with ADHD; 69 children with ADHD and common comorbidities (28 anxiety, 12 autism spectrum disorder/ASD,[1] 4 depression, 11 oppositional-defiant disorder/ODD, and 28 specific learning disorders); 21 with common clinical diagnoses but not ADHD (13 anxiety, 7 ASD, 4 depression, and 1 specific learning disorder); and 28 neurotypical children (Table 1). Psychostimulants ($N_{prescribed}$= 42; 27.8%) were withheld ≥24 hours for neurocognitive testing. Psychoeducational evaluations were provided to caregivers. Children were excluded if they presented with gross neurological, sensory, or motor impairment; non-stimulant medications that could not be withheld for testing; or history of seizure disorder, psychosis, or intellectual disability.

Procedures

Children participated in 1-2 research sessions (approximately 3 hours each) following the baseline psychoeducational assessment. The executive function tasks were administered as part of a larger battery of laboratory tasks that were counterbalanced within and across sessions to minimize order effects. Performance was monitored at all times by the examiner, who was stationed just out of the child's view to provide a structured setting while minimizing performance improvements associated with examiner demand characteristics (Gomez & Sanson, 1994). All children received brief breaks after each task and preset longer breaks after every 2-3 tasks to minimize fatigue.

Measures

Working Memory Tasks

Rapport Visuospatial Reordering Task.: The Rapport visuospatial working memory test and administration instructions are identical to those described in Kofler et al. (2018). Psychometric support includes high internal consistency (α=0.81-0.97) and 1-3-week test-retest reliability (0.76-0.90; Kofler et al., 2019; Sarver et al., 2015), and expected relations with criterion working memory complex span (r=0.69) and updating tasks (r=0.61; Wells et al., 2018). Children were shown nine squares arranged in three offset vertical columns. A series of 2.5 cm diameter dots (3, 4, 5, or 6) were presented sequentially in one of the nine squares during each trial, such that no two dots appeared in the same square on a given trial. All but one dot presented within the squares was black—the exception being a red dot that was counterbalanced across trials to appear an equal number of times in each of the nine squares, but never presented as the first or last stimulus in the sequence to minimize potential primacy and recency effects. Children reordered the dot locations (black dots in

[1]The pattern and interpretation of results was unchanged with participants with ASD excluded, with two minor exceptions noted in the Sensitivity Analyses section below.

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serial order, red dot last) and responded on a modified keyboard. Six trials per set size were administered in randomized/unpredictable order (3-6 stimuli/trial; 1 stimuli/second) as recommended (Kofler et al., 2016). Five practice trials were administered before each task (80% correct required). Partial-credit unit scoring (i.e., stimuli correct per trial) was used as recommended (Conway et al., 2005). Higher scores reflect better working memory.

Letter Updating Task.: The letter updating working memory test and administration instructions are identical to those described in Fosco et al. (2019). Psychometric support includes high internal consistency (α=0.75), expected magnitude relations with other working memory tests (Kofler et al., 2018), and large magnitude ADHD/Non-ADHD between group differences (Fosco et al., 2019; Kofler et al., 2018). In this computerized task, letters were presented on the screen one at a time, and children were instructed to keep track of the last three letters presented. To ensure the task required continuous updating, children were instructed to rehearse out loud the last three letters by mentally adding the most recent letter and dropping the fourth letter back and then saying the new string of three letters out loud (Miyake et al., 2000). The number of letters presented (4-8 stimuli presented/trial, 1200 ms presentation, 2400 ms ISI) was varied randomly across trials to ensure that successful performance required continuous updating until the end of each trial. A practice block was administered; children advanced to the test phase following three correct practice trials. Four blocks of three test trials each were administered. Children responded via mouse click. Higher stimuli correct per trial reflects better working memory.

Counting Span Task.: The counting span dual-processing working memory test and administration instructions are identical to those described in Fosco et al. (2019). Psychometric support includes high internal consistency (α=0.86), expected magnitude relations with other working memory tests, and large magnitude ADHD/Non-ADHD between group differences (Fosco et al., 2019). Children were sequentially shown screens containing a random number of black dots and between 1 and 9 red dots (all 2.5 cm diameter). Children were instructed to verbally report the number of red dots as each screen was presented, ignoring the black dots. After a predetermined number of screens (set sizes 3, 4, 5, and 6), children were asked to indicate via mouse click the number of red dots on each screen in serial order. As such, the task places demands on working memory by introducing dual processing demands using the same modality (phonological), as participants counted dots on each screen while recalling the number of red dots on previous screens. Each screen was displayed for 500 ms per red dot (e.g., screens with 6 red dots remained visible for 3000 ms; ISI = 500 ms). Sixteen total trials (4 per set size, presented randomly) were completed following a practice round that terminated after two correct trials. Higher stimuli correct per trial reflects better working memory.

Inhibitory Control Tasks

Stop-signal Inhibitory Control.: The stop-signal test and administration instructions are identical to those described in Alderson et al. (2008). Psychometric evidence includes high internal consistency (✓=0.80; Kofler et al., 2018) and three-week test-retest reliability (0.72), as well as convergent validity with other inhibitory control measures (Soreni et al., 2009). Go-stimuli are displayed for 1000 ms as uppercase letters X and O positioned in the center of a computer screen (500 ms interstimulus interval; total trial duration = 1500 ms). Xs and Os appeared with equal frequency throughout the experimental blocks. A 1000 Hz auditory tone (i.e., stop-stimulus) was presented randomly on 25% of trials. Stop-signal delay (SSD)—the latency between presentation of go- and stop-stimuli—is initially set at 250 ms and dynamically adjusted ± 50 ms contingent on participant performance. Successfully inhibited stop-trials are followed by a 50 ms increase in SSD, and unsuccessfully inhibited stop-trials are followed by a 50 ms decrease in SSD. All participants completed two practice blocks and four consecutive experimental blocks of 32 trials per block (24 go-trials, 8 stop-trials per block). SSD across the four tasks blocks was selected based on conclusions from recent meta-analytic reviews that it is the most direct measure of inhibitory control in stop-signal tasks that utilize dynamic SSDs, given that SSDs change systematically according to inhibitory success or failure (Alderson et al., 2007; Lijffijt et al., 2005)[2]. Higher SSD scores indicate better inhibitory control.

Go/no-go Inhibitory Control.: The go/no-go test and administration instructions are identical to those described in Kofler et al. (2018). Psychometric evidence includes high internal consistency (✓=0.95) as well as convergent validity with other inhibitory control measures (Kofler et al., 2018). Children were presented a randomized series of vertical (go stimuli) and horizontal (no-go stimuli) rectangles in the center of a computer monitor (2000 ms presentation, jittered 800–2000 ms ISI to minimize anticipatory responding). They were instructed to quickly click a mouse button each time a vertical rectangle appeared, but to avoid clicking the button when a horizontal rectangle appeared. A ratio of 80:20 go:no-go stimuli was selected to maximize prepotency (Kane & Engle 2003; Unsworth & Engle 2007). Children completed a 10-trial practice (80% correct required) followed by 4 continuous blocks of 25 trials each. Commission errors reflect failed inhibitions (i.e., incorrectly responding to no-go trials), and served as the primary index of inhibitory control during each of the four task blocks. Mean commission errors per block was computed; lower scores indicate better inhibition.

Set Shifting Tasks

Global-local Set Shifting.: The global-local test and administration instructions are identical to those described in Irwin et al. (2019). Psychometric evidence includes high internal consistency (✓=0.86-0.90) as well as convergent validity with other set shifting measures (Kofler et al., 2018). This task uses Navon (1977) figures, which feature a “global” shape (e.g., a circle) constructed using smaller, “local” figures (e.g., squares). Figures were presented one at a time in one of four quadrants (clockwise rotation) on a computer monitor (jittered ISI 800-2000ms). To minimize memory demands, on-screen cues (“big shape”, “small shapes”) were positioned next to each quadrant. Following three blocks of 6 to 8 practice trials (100% correct required), children completed 4 consecutive blocks of 15 trials each. Children were required to shift their response between global and local features depending on the quadrant in which the figures appeared (top quadrants: global; bottom quadrants: local). Trials with stimuli in the top left or bottom right quadrants involved

[2]Stop-signal reaction time (SSRT) was also computed due to debate regarding the optimal metric for estimating inhibitory control from the stop-signal task. When substituted for SSD, SSRT failed to load with the inhibitory control variable from the go/no-go task when factor analyzed and was therefore excluded from further analysis.

set shifting (shift trials) because responses required a different rule than the previous trial; trials with stimuli in the top right or bottom left quadrants did not require shifting because they featured the same rule as the previous trial (non-shift trials). Set shifting abilities were operationalized as accuracy shift costs (accuracy shift cost=$\%Errors_{Shift}$-$\%Errors_{non\text{-}shift}$) and speed shift costs (speed shift cost = $RT_{shift} - RT_{non\text{-}shift}$ for correct trials) as recommended (Miyake et al., 2000). Lower shift costs reflect better set shifting.

Number-color Set Shifting.: The number-color set shifting test and administration instructions are identical to those described in Kofler et al. (2019). Psychometric evidence includes high internal consistency (✓=0.87-0.95) as well as convergent validity with other set shifting measures (Kofler et al., 2018). A pair of single-digit numbers appeared on the screen, and children were instructed to click either the larger or smaller value depending on the font color (blue = bigger, yellow = smaller; colors selected for maximal discrimination across individuals with all types of color vision). Both digits were the same color on any given trial. To minimize memory demands, on-screen instructions ("blue bigger, yellow smaller") remained visible throughout the task. Following an 8-trial practice block (100% correct required), children completed 4 consecutive blocks of 30 trials each (120 total trials; jittered ISI 80-200 ms). Trials were presented in a semi-random sequence to require shifting every other trial, with an equal number of bigger-smaller and smaller-bigger shifts. Accuracy and RT data were recorded separately for 'shift' and 'non-shift' trials, and processed identically to the global-local data described above. Lower shift costs reflect better set shifting.

Executive Function Dimension Reduction

Task impurity was controlled by computing Bartlett maximum likelihood component scores based on the intercorrelations among task performance scores (DiStefano et al., 2009), which parsed the 3 working memory, 2 inhibitory control, and 2 set shifting tasks into three component scores (31.10% of variance explained; Supplementary Table 1). A three-component solution was specified *a priori* to derive separate estimates of working memory, inhibitory control, and set shifting based on theory and previous empirical work (e.g., Miyake et al. 2000). These principal components analysis-derived component scores provide estimates of reliable, construct-level variance attributable to domain-general working memory, inhibitory control, and set shifting, respectively. This formative method for estimating executive functioning was selected because such methods have been shown to provide higher construct stability relative to confirmatory/reflective approaches (Willoughby et al., 2016). By design, the intercorrelations among the varimax-rotated working memory, inhibitory control, and set shifting components were $r_{all} = 0.00$ ($p > 0.99$). Conceptually, this process isolates reliable variance attributable to each executive function by removing task-specific demands associated with nonexecutive processes and non-construct variance attributable to each of the other two executive functions. These component scores were used in all analyses. Higher scores reflect better working memory, but worse inhibitory control and set shifting.

ADHD Symptoms

ADHD Rating Scale (ADHD-RS-4/5): The ADHD-RS-4/5 (Du Paul et al., 2016) was used to assess the frequency and severity of ADHD symptoms based on DSM criteria in children and adolescents aged 5 to 17 (18 items; 4-point Likert scale). The ADHD-RS-4/5 comprises two symptom subscales: Inattention (9 items) and Hyperactivity-Impulsivity (9 items). Psychometric support for the ADHD-RS-4/5 includes high internal consistency (α=0.94) and test-retest reliability (r= 0.79 to 0.85; DuPaul et al., 2016). Teacher-reported ADHD symptoms were selected *a priori* to reduce mono-informant bias, as parent report was used to measure emotion regulation, and because teacher ratings may outperform parent ratings when classifying children with and without ADHD (Tripp, Schaughency, & Clarke, 2006). Higher raw scores reflect greater quantity/severity of ADHD symptoms.

Emotion Regulation

Emotion Regulation Checklist (ERC): The ERC (Shields & Cicchetti, 1997) was used to assess children's emotion regulation based on parent report (24 items; 4-point Likert scale). Psychometric support for the ERC includes high internal consistency (α=0.98), discriminant validity relative to distinct constructs such as resilience, expected relations with other metrics of emotion regulation (r=0.44-0.79), and the ability to differentiate between groups of children at-risk for emotional problems and typically developing children (Shields & Cicchetti, 1997). Higher raw scores reflect better emotion regulation.

Global Intellectual Functioning (IQ) and Socioeconomic Status (SES)

IQ was estimated using the Verbal Comprehension Index of the WISC-V (Wechsler, 2014). Hollingshead (1975) SES was estimated based on caregiver(s)' education and occupation.

Data Analysis Plan

The study's primary analyses used jamovi (version 1.1; the jamovi project, 2019) with 1,000 bootstrapped samples to examine the bias-corrected relations among the variables of interest. Using path analysis, each of the executive functions were modeled concurrently as predictors of ADHD inattention, ADHD hyperactivity/impulsivity, and emotion regulation. Further, the ADHD symptom clusters were modeled as predictors of emotion regulation. Inattention and hyperactivity/impulsivity were included separately based on evidence that they differentially predict relations between working memory and other ADHD-related impairments (e.g., Bunford et al., 2014). Pathway directionality was specified *a priori* given the evidence reviewed above that executive functions, particularly working memory and inhibitory control, are often conceptualized as underlying causal factors contributing to the ADHD phenotype. In addition, the ADHD symptom clusters were modeled as predictors of emotion dysregulation given conceptualizations of emotion regulation difficulties as secondary features of ADHD (Graziano & Garcia, 2016). Finally, the executive functions were modeled as a predictors of emotion regulation, rather than vice versa, because preponderance of evidence support effects in this direction (e.g., Schmeichel et al., 2008; Schmeichel & Tang, 2015). Effects are considered statistically significant if their 95% confidence intervals (CIs) do not contain zero. Effect ratios (ER) for significant indirect effects indicate the proportion of the total effect (c pathway) that is conveyed via the indirect pathway (ab; i.e., ER=ab/c).

Results

Power Analysis

Large effects were predicted based on large relations between emotion regulation and ADHD symptoms (d = 0.80–0.95; Graziano & Garcia, 2016) and moderate-to-large relations between executive functions and ADHD symptoms (e.g., d = 0.46 to 2.0; Kasper et al., 2012, Kofler et al., 2018). Our N of 151 exceeds the N = 34 required for bias-corrected bootstrapping to detect an effect of these expected magnitudes for α = 0.05 and power = 0.80 with one predictor and one intermediate effect (Fritz & MacKinnon, 2007). Conservatively assuming partial mediation and approximately equal contributions of each mediator, N = 100 produced power =0.94-0.96 to detect the total indirect effect for each independent variable with two intermediate effects (Briggs, 2006). Power for detecting significance for each intermediate effect with N = 100 was 0.92-0.94. Thus, the current study's N of 151 is adequately powered to detect effects of the expected magnitude.

Preliminary Analyses

Each of the independent and dependent variables were screened for univariate outliers, defined as values greater than 2 interquartile ranges outside of the median. Four percent of data points from the ADHD group and 3% of data points from the Non-ADHD group were identified as outliers and were corrected to the most extreme value within 2 interquartile ranges of the median. Missing data were determined to be missing completely at random (Little's MCAR test: χ^2 = 38.55, p>0.99) and were imputed using expectation maximization based on all available data. This process affected 0.16% of data points. Task data from subsets of the current battery have been reported for subsets of the current sample to examine conceptually unrelated hypotheses in Kofler et al. (2018a-d). A subset of the current sample was included in our previous study of working memory and emotion regulation as noted above (Groves et al., 2020). There is no overlap between that study and the current study in terms of ADHD symptom measures, emotion regulation skills measures, or 6 of the current study's 7 executive function tests.[3]

Primary Analyses

Results of the bias-corrected bootstrapped conditional effects model are shown in Fig. 1 and Supplementary Table 2, and indicated that better developed working memory predicted better emotion regulation (β = 0.23, b = 1.93, 95% CI = 0.62 to 3.24). In contrast, there was no evidence for relations between inhibitory control (β = −0.04, b = −0.33, 95% CI = −1.65 to 0.98) or set shifting (β = 0.12, b = 1.00, 95% CI = −0.31 to 2.31) and emotion regulation.

[3]The Rapport visuospatial working memory test used in Groves et al. (2020) was also included in the current study to provide broad coverage of all three 'working' components of working memory (see Fosco et al., 2019) and ensure that our derived working memory component reflected working memory rather than phonological storage/rehearsal as might have occurred if only including phonological tasks (Baddeley, 2007). None of the current study's other 6 tests were included in our previous study. The current study used the criterion executive functioning battery recommended by Kofler et al., (2018); the battery was selected *a priori*, prior to accessing the data, with researchers masked to the effects on study results.

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Additionally, better developed working memory predicted fewer inattentive ($\beta = -0.37$, $b = -2.63$, 95% CI = −3.72 to −1.48) and hyperactive/impulsive symptoms ($\beta = -0.21$, $b = -1.70$, 95% CI = −2.87 to −0.26). Inhibitory control was not independently related to inattentive ($\beta = -0.08$, $b = -0.58$, 95% CI = −1.63 to 0.39) or hyperactive/impulsive ($\beta = -0.03$, $b = -0.23$, 95% CI = −1.46 to 0.90) symptoms, and set shifting skills also did not predict ADHD symptoms (inattention: $\beta = -0.09$, $b = -0.63$, 95% CI = −1.53 to 0.15; hyperactivity/impulsivity: $\beta = 0.02$, $b = 0.16$, 95% CI = −1.43 to 1.37). Greater inattention ($\beta = -0.18$, $b = -0.22$, 95% CI = −0.41 to −0.003) and hyperactivity/impulsivity ($\beta = -0.20$, $b = -0.20$, 95% CI = −0.38 to −0.03) both predicted worse emotion regulation skills when controlling for the effects of working memory, inhibitory control, and set shifting. Indirect effects of working memory on emotion regulation were significant via both the inattention ($\beta = 0.07$, $b = 0.57$, 95% CI = 0.06 to 1.26, ER = 0.30) and hyperactivity/impulsivity ($\beta = 0.04$, $b = 0.34$, 95% CI = 0.05 to 0.89, ER = 0.18) pathways, indicating that 30% and 18% of working memory's relation with emotion regulation is shared with ADHD inattentive and hyperactive/impulsive symptoms, respectively. Finally, the direct relation between working memory and emotion regulation was no longer significant after accounting for working memory's indirect impact on emotion regulation skills via the ADHD symptoms pathways (c' pathway: $\beta = 0.12$, $b = 1.02$, 95% CI = −0.27 to 2.35). Overall, the model explained R^2=0.15 of the variance in ADHD inattention, R^2=0.04 of the variance in ADHD hyperactivity/impulsivity, and R^2=0.16 of the variance in emotion regulation.

Sensitivity Analyses

A series of sensitivity analyses were conducted to determine the extent to which results may have been impacted by our *a priori* decisions to (a) use an orthogonal rotation for the executive function factor scores in the primary analyses; (b) use raw scores uncorrected for age and sex in the primary model; and (c) include children with ASD in the sample. First, we repeated the primary model above, this time using executive function component scores derived via oblique rotation. The pattern of results was unchanged when allowing the executive function factors to correlate (Supplementary Table 3). Of note, the obliquely-rotated working memory and inhibitory control factors were correlated (r=0.43, p<0.001), but the working memory and set shifting (r=−0.01, p>0.05) and inhibitory control and set shifting component scores (r=0.06, p>0.05) were not significantly correlated with one another. Next, we repeated the primary model again, this time covarying age and sex. The pattern of results was once again highly consistent, with three minor exceptions: the indirect effect of working memory on emotion regulation via the hyperactive/impulsive pathway was no longer significant (β changed from 0.04 to 0.03), the direct effect of inattentive symptoms on emotion regulation was no longer significant (β changed from −0.18 to −0.15; both 95%CIs include 0.0), and the direct effect of working memory on emotion regulation remained significant after accounting for the ADHD symptom pathways (β increased from 0.12 to 0.21; 95%CI excludes 0.0; Supplementary Table 4). Finally, we repeated the primary model again, this time excluding participants diagnosed with ASD (n=132 remaining) given that emotion regulation difficulties may be qualitatively different for these children (Mazefsky & White, 2014). Results were once again highly consistent with the initial model, with two minor exceptions: the indirect effect of working memory on emotion regulation via the inattentive symptoms pathway was no longer significant

(β changed from 0.07 to 0.06), and inattentive symptoms no longer predicted emotion regulation after controlling for the executive functioning variables (β changed from −0.18 to −0.16; both 95% CIs include 0.0; Supplementary Table 5). In all cases, the total effect of working memory on emotion regulation remained significant (c pathways; β=0.17-0.29), whereas there was no evidence for effects of inhibitory control or set shifting in any tested model.

Discussion

The current study was the first to examine the extent to which all three primary executive functions (Miyake et al., 2000) and both ADHD symptom clusters predict children's emotion regulation skills. Additional strengths of the study included the use of multiple tasks and informants, as well as a carefully evaluated and clinically diverse sample of children with and without ADHD. Findings from the current study indicate that better-developed working memory, but not inhibitory control or set shifting, predicts fewer ADHD symptoms and better emotion regulation skills. This finding is consistent with previous literature that demonstrates that working memory predicts ADHD symptom severity both cross-sectionally (Gathercole et al., 2008; Hudec et al., 2015; Kofler et al., 2010; Patros et al., 2015; Raiker et al., 2012; Rapport et al., 2009) and longitudinally (Halperin et al., 2008; Karalunas et al., 2017; Salari et al., 2017; van Lieshout et al., 2016), as well as research demonstrating that working memory capacity predicts emotion regulation skills in neurotypical samples (e.g., Schmeichel et al., 2008) and in children with ADHD (Groves et al., 2020).

In contrast, at first glance, the lack of relation between inhibitory control and emotion regulation was surprising given that this association is present in most (Carlson et al., 2007; Falquez et al., 2015; Feng et al., 2008; Ferrier et al., 2014; Hoeskma et al., 2004; Hendricks et al., 2016; Leen-Feldner et al., 2004; Sjowall et al., 2013; Tenenbaum et al., 2019) albeit not all previous studies (Gyuark et al., 2012). However, as noted below, working memory difficulties have been posited as a mechanism that produces diminished performance on inhibition tasks for children with ADHD (e.g., Alderson et al., 2010). In that context, the discrepancy between our findings and most prior work may be because we were able to statistically remove aspects of children's inhibition task performance that are due to the significant but unintended working memory demands imposed by these tasks (i.e., task impurity; Miyake et al., 2000). Similarly, the findings that set shifting did not predict ADHD symptoms or emotion regulation contribute to an already mixed body of literature in which set shifting abilities are sometimes associated with ADHD symptoms (Willcutt, 2005) or emotion regulation (De Lissnyder et al., 2010; Gul & Khan, 2014; Hughes et al., 1998; Johnson, 2009; Martins et al., 2016; Moreira et al., 2019; Murphy et al., 2012), but often do not appear to contribute significantly to the ADHD phenotype (Irwin et al., 2019) or emotion regulation skills (Aker et al., 2014; Fuster et al., 2009). Overall, findings from this study underscore the importance of working memory relative to the other primary executive functions in the prediction of both ADHD symptoms and emotion regulation skills. This interpretation is consistent with models of ADHD as well as models from the cognitive literature that emphasize the role of working memory in ADHD-related impairments overall

(Bunford et al., 2014; Kofler et al., 2011; Rapport et al., 2008; Rennie et al., 2014), and in emotion regulation difficulties specifically (Groves et al., 2020; Tarle et al., 2021).

Interestingly, inattentive and hyperactive/impulsive symptoms both uniquely predicted emotion regulation, even when controlling for executive functioning, and 18%-30% of working memory's relation with emotion regulation was conveyed via shared associations with these ADHD symptoms. This pattern suggests that working memory is related to emotion regulation at least in part because underdeveloped working memory contributes to the development and severity of ADHD symptoms (e.g., Karalunas et al., 2017; Kofler et al., 2009), which, in turn, predicts emotion dysregulation. Working memory's overall association with emotion regulation replicates previous research (e.g., Schweizer et al., 2017; Tarle et al., 2021). In contrast, our primary model finding that the working memory/ emotion regulation relation became nonsignificant after accounting for ADHD symptoms was somewhat inconsistent with previous research based on part on a subset of the current sample (Groves et al., 2020). This discrepancy may be related to our use of more specific emotion regulation and ADHD symptom scales in the current study relative to the potentially less sensitive subscale from a broadband screening questionnaire in our previous study. Alternatively, our sensitivity analyses suggest that this discrepancy may be relate to our *a priori* decision to conduct our primary model without covariates; with age and sex controlled, the findings replicated those of our previous study more closely and suggest that working memory is related to emotion regulation both independently and via its shared associations with ADHD symptoms.

Taken together, the current findings suggest at least three independent pathways to emotion regulation difficulties: (1) emotion dysregulation that reflects the behavioral expression of underdeveloped working memory, as evidenced by the significant direct and indirect effects of working memory on emotion regulation; (2) emotion dysregulation secondary to additional aspects of the ADHD syndrome unrelated to underlying executive functioning deficits, as evidenced by significant effects of ADHD symptoms in most tested models even after controlling for executive functioning; and (3) emotion dysregulation independent of all neurocognitive and behavioral mechanisms tested in the current study, as evidenced by our primary model accounting for approximately 16% of the variance in emotion regulation. This evidence for multiple pathways to emotion dysregulation is consistent with work acknowledging the multidimensionality of executive functions (e.g., Miyake et al., 2000), ADHD symptoms (e.g., Luo et al., 2019), and emotion regulation (e.g., Gross, 1998).

Limitations and Future Directions

The current study has many strengths, including a relatively large, carefully evaluated, and clinically diverse sample and our use of multiple measures, tasks, and informants. However, results should be interpreted with consideration to the following limitations. First, the use of other-informant measures of emotion regulation is informative in that they assess emotion regulation using behaviors observable to caregivers, rather than relying on children's introspective self-report that may be hindered by limited insight, particularly in light of replicated evidence that children with ADHD reliably underreport their own symptoms and impairments (Langberg et al., 2013; Owens et al., 2007). Nonetheless, these measures are limited in their ability to disentangle the mechanisms underlying emotionally dysregulated behavior, as these behaviors may be caused by deficits in emotion regulation, increased emotional reactivity or lability, or some combination of these factors. Although this study focused on the behavioral manifestation of emotion dysregulation, there is evidence that emotional reactivity and regulation may represent the same construct (Zelkowitz & Cole, 2016). Both processes are impaired in children with ADHD (Graziano & Garcia, 2016) and have been implicated as potential explanations of emotion dysregulation in ADHD (e.g., Christiansen et al., 2019; Graziano & Garcia, 2016). Future research should investigate emotion regulation using more objective measures of emotion regulation subcomponents (e.g., physiological indicators of emotional reactivity) and/or examining self-reported cognitive-behavioral strategies used to regulate emotions in children with ADHD. Additionally, the clinical diversity of the sample was useful given that comorbidity is the rule rather than the exception in individuals with ADHD (e.g., Reale et al., 2017), but the inclusion of comorbidities may limit the specificity of these findings regarding children with only ADHD. Given that emotion dysregulation portends risk for the development of comorbidities (Steinberg & Drabick, 2015), recruitment of samples that allow for comparisons between groups of children with ADHD with and without comorbid diagnoses may be useful. Finally, longitudinal work is needed to clarify the interplay of these constructs over time.

Clinical Implications

The present study suggests multiple potential pathways to ADHD-related emotion dysregulation and is consistent with previous work in underscoring the importance of working memory for understanding ADHD symptom severity (Halperin et al., 2008; Karalunas et al., 2017; Salari et al., 2017; van Lieshout et al., 2016) and emotion regulation skills (Groves et al., 2020; Tarle et al., 2021). When studied in isolation, all three executive functions have been linked with emotion regulation skills; however, the current findings suggest that only working memory abilities uniquely covary with children's emotion regulation skills, and that this relation is driven in part by working memory's influence on ADHD behavioral symptoms, which, in turn, predict emotion regulation skills. Consideration of this specificity in the relation between executive functions and emotion regulation will be important for developing and refining interventions that target emotion dysregulation in ADHD, and suggest that targeting working memory may be helpful for producing downstream effects on emotion regulation. At the same time, the model R^2 suggests that fairly large changes in working memory would be needed to produce clinically meaningful improvements in emotion regulation, and, as such, combined neurocognitive training and skills training may provide maximal benefits (Chacko et al., 2014). Alternatively, these results may be useful for the modification of extant psychotherapy techniques, as they suggest that providing additional scaffolding for underdeveloped working memory (e.g., through written reminders, provision of brief, single-step instruction, repetition of material to-be-remembered) may provide better emotion regulation outcomes, particularly for children who exhibit inattentive and hyperactive/ impulsive symptoms. Finally, findings from the current study revealed at least three pathways to emotion dysregulation, consistent with well-documented heterogeneity in deficits and functional outcomes in children with ADHD (Nigg et al., 2020), and such heterogeneity emphasizes the need for comprehensive assessment and a precision medicine approach to the treatment of ADHD and its associated difficulties, including emotion regulation.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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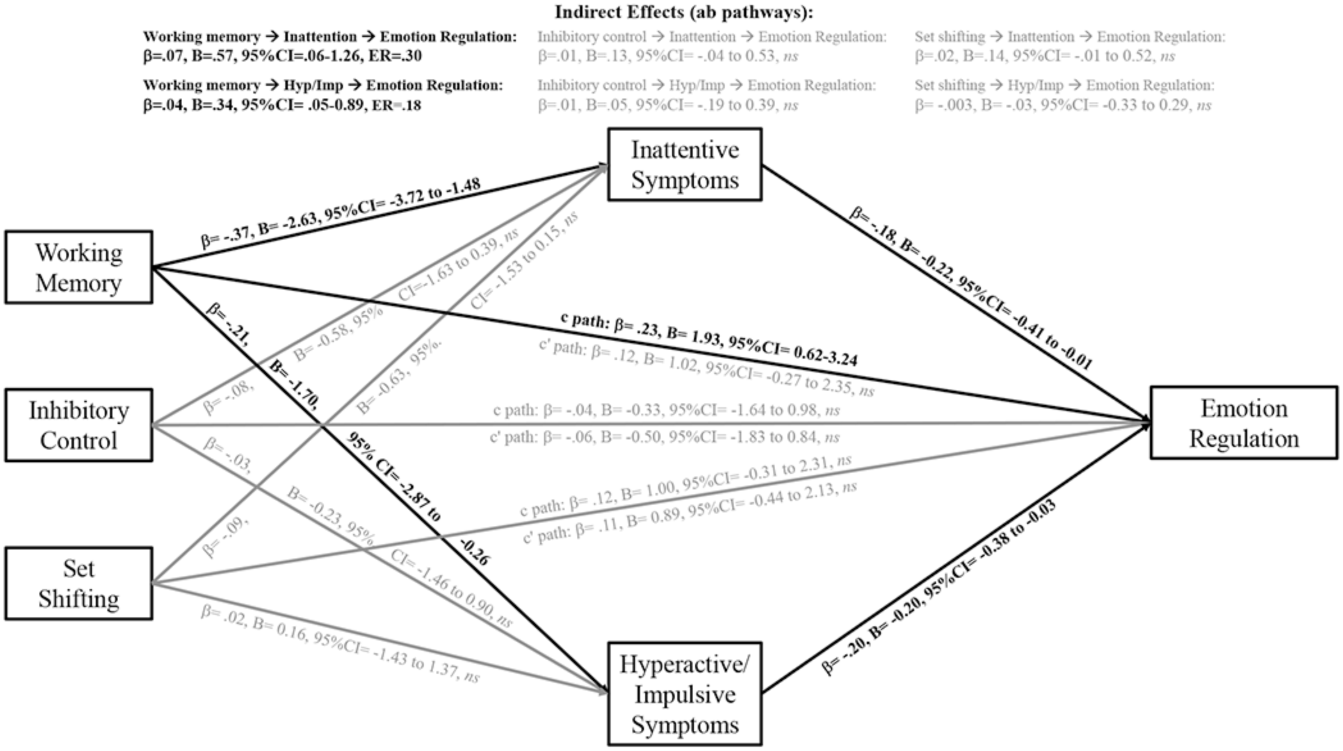

Fig. 1.

Path diagram depicting primary model results. Significant pathways are indicated by 95% CIs that exclude zero, and are shown in black/bold font. Nonsignificant pathways are shown in grey font

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Table 1

Sample and demographic variables

Variable	ADHD		Non-ADHD		Cohen's *d*	*t*	χ^2	*p*
	M	***SD***	***M***	***SD***				
N (Boys/Girls)	102 (70/32)		49 (29/20)		--	--	1.31	0.25, *ns*
Age	10.14	1.46	10.82	1.55	0.46	2.62	--	0.01
SES	48.22	11.21	49.94	11.68	--	0.87	--	0.39, *ns*
VCI	103.95	13.73	108.59	11.21	0.36	2.06	--	0.04
Race/Ethnicity (W, B, H, MR, A)	(77, 13, 7, 5, 0)		(29, 5, 6, 8, 1)		--	--	9.65	0.05, *ns*
Working Memory Component Score	−0.40	0.85	0.84	0.74	1.52	8.81	--	<0.001
Inhibitory Control Component Score	−0.05	1.03	0.10	0.93	0.15	0.83	--	0.41, *ns*
Set Shifting Component Score	0.07	1.11	−0.14	0.71	0.21	1.41	--	0.16, *ns*
Emotion Regulation Checklist (Total Raw Score)	69 04	8.29	75.47	7.21	0.81	4.64	--	<0.001
ADHD-RS-4/5 Inattention (Total Raw Score)	16.92	5.95	10.51	7.54	0.99	5.22	--	<0.001
ADHD-RS-4/5 H/I (Total Raw Score)	11.74	8.18	6.55	7.32	0.66	3.77	--	<0.001

Executive function component scores are z-scores relative to the current sample

A Asian, *ADHD-RS-4/5* ADHD Rating Scale-4/5, *B* Black, *H* Hispanic/Latino, *H/I* Hyperactivity/Impulsivity, *MR* Multiracial, *SES* Hollingshead SES total score, *VCI* Wechsler Verbal Comprehension Index, *W* White/Non-Hispanic