IMPAIRED WORKING MEMORY

AND ADHD-RELATED

EMOTION REGULATION DEFICITS

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Abstract: Meta-analytic reviews have found large-magnitude deficits in emotion regulation (Graziano & Garcia, 2016) and working memory (Kasper et al., 2012) when comparing children with and without attention-deficit/hyperactivity disorder (ADHD). Further, previous studies that have examined ADHD-related emotion regulation and working memory deficits relied exclusively on rating scales to measure emotion regulation and working memory tasks that placed insufficient demands on central executive processes. The current study, in contrast, coded behavioral observations of emotion regulation behaviors while children with and without ADHD completed control conditions (i.e., low working memory demands) and working memory tasks (i.e., high working memory demands). Children with ADHD exhibited large-magnitude overall emotion expression deficits compared to controls. Interaction effects were observed for behaviors of self-criticism/negative self-talk, emotion ventilation, and positive emotion expression. Children with ADHD, compared to controls, exhibited disproportionately greater self-criticism and emotion ventilation when working memory demands were increased, as well as disproportionately greater positive emotion expression when working memory demands decreased. This is the first study to demonstrate that ADHD-related working memory impairments underlie deficits in regulating negative emotions. The findings from this study may help to improve clinical interventions and assessments of ADHD-related emotion regulation.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Attention-deficit/hyperactivity disorder (ADHD) is a complex, highly heritable, and lifelong disorder that is characterized by symptoms of inattention, impulsivity, and hyperactivity (American Psychiatric Association [APA], 2013; Barkley, 2006). The prevalence of ADHD within the United States is approximately 7% of children (Thomas, Sanders, Doust, Beller, & Glasziou, 2015), and an average of 36 billion dollars is spent on the disorder each year (Erskine et al., 2014). Moreover, children with ADHD are at higher risk for comorbid behavior and/or mood disorders (Jensen, Martin, & Cantwell, 1997), learning disorders (Daley & Birchwood, 2009), physical injury (Barkley, 2006), peer rejection (Hoza et al., 2005), and impairments in regulating emotions (Graziano & Garcia, 2016).

Emotion regulation is the ability to generate and maintain an emotion, as well as the ability to decrease an emotion's intensity and/or frequency (Cole, Michel, & O'Donnell, 1994; Gross, 1998). Emotion regulation is related to the development and refinement of executive functions/high-order neurocognitive processes, such as inhibition, planning, and working memory (Hofmann, Schmeichel, & Baddeley, 2012). Across the lifespan, for example, children use inhibition to down regulate their emotions based on social norms (e.g., Gross, 2002; Thompson, 1994), and use working memory to interpret co-occurring or complex emotions by recognizing emotional expressions, considering the context of a situation, and deciding how to modulate their own responses (e.g., Ochsner & Gross, 2005; Schmeichel, 2007). Within the context of ADHD, a recent meta-analytic review found that affected children, compared to typically developing (TD) children, exhibit large-magnitude emotion regulation deficits ($d = 0.80$) that persist when controlling for the presence of cognitive functioning (Graziano & Garcia, 2016). Collectively, these findings suggest that emotion regulation deficits are a distinct feature of ADHD and not merely associated with the presence of cognitive deficits.

Etiological causes of ADHD-related emotion regulation difficulties are unclear, but several ADHD models suggest other neurocognitive deficits underlie emotion regulation difficulties. Barkley's (1997) inhibition model of ADHD, for example, suggests that impaired behavioral inhibition leads to deficits in other executive functions such as working memory, planning, and self-regulation of affect. That is, Barkley's model predicts an indirect effect of inhibitory deficits on the ADHD phenotype through self-regulation of affect. Walcott and Landau's (2004) findings, however, indicate that behavioral disinhibition is a weak predictor of ADHD-related emotion regulation deficits, and suggest other executive functions may serve as stronger candidate core features of the disorder's primary (i.e., inattention and hyperactivity/impulsivity) and tertiary (e.g., self-regulation impairments) symptoms (e.g., Berlin, Bohlin, Nyberg, & Janols, 2004).

In contrast, Rapport et al.'s (2008) functional working memory model hypothesizes that the ADHD phenotype results from impaired working memory, which serves as a central core deficit of the disorder. Support for the model is provided by extant research that indicates ADHD-related working memory deficits are causally related to increased motor activity (Rapport et al., 2009) and underlie DSM-5-defined core symptoms such as disinhibition (Alderson, Rapport, Hudec, Sarver, & Kofler, 2010), inattention (Kofler, Rapport, Bolden, Sarver, & Raiker, 2010), and impulsivity (Patros, Alderson, Hudec, Tarle, & Lea, 2017). Not surprisingly, previous research suggests that working memory deficits also contribute to secondary symptoms of the disorder, such as social problems (Kofler et al., 2011) and academic underachievement (Rogers, Hwang, Toplak, Weiss, & Tannock, 2011). It stands to reason, therefore, that ADHD-related working memory deficits might also underlie emotion regulation difficulties. Indeed, findings from basic cognitive research suggest that working memory assists with decoding emotions (Phillips, Channon, Tunstall, Hedenstrom, & Lyons, 2008), emotional responding (Schmeichel, Volokhov, & Demaree, 2008), and distraction from negative moods (Van Dillen & Koole, 2007), and a recently proposed cognitive model suggests domain-specific components of working memory (i.e., a maintenance subsystem or episodic buffer specialized for emotions) serve to maintain emotion-related information (Mikels, Reuter-Lorenz, Beyer, & Fredrickson, 2008).

Relatively few studies (Berlin et al., 2004; Sjöwall, Roth, Lindqvist, & Thorell, 2013; Sjöwall, Backman, & Thorell, 2015; Wåhlstedt, Thorell, & Bohlin, 2008) have examined the relationship between working memory and emotion regulation in children with ADHD. Correlational studies have yielded evidence of small-magnitude associations between working memory and the regulation of positive and negative emotions (Sjöwall et al., 2013, 2015), but have been equivocal with respect to identifying working memory as a predictor of group membership (Berlin et al., 2004; Sjöwall et al., 2013; 2015). For example, previous findings have identified working memory and emotion regulation as significant predictors of unique variance associated with group membership (Berlin et al., 2004) and ADHD symptoms (Sjöwall et al., 2015). In contrast, Sjöwall and colleagues (2013) found emotion regulation, but not working memory, predicted group membership. Finally, Wåhlstedt and colleagues' (2008) longitudinal study utilized a non-clinical sample and non-correlational design and found that ADHD symptoms, but not executive functioning, affected problems with emotion regulation at a two-year follow up.

Inferences drawn from previous studies about the relationship between ADHD-related working memory and emotion regulation deficits may be incomplete due to several methodological limitations. First, previous studies utilized measures of working memory, such as digit span backwards (Sjöwall et al., 2013, 2015; Wåhlstedt et al., 2008) and forward span visual-spatial tasks (Wåhlstedt et al., 2008), that at best provide a metric of short-term memory processes and place insufficient demands on the *working* component of working memory (i.e., central executive processes; Moleiro et al., 2013). To that end, the null association between working memory and later emotion regulation found in Wåhlstedt and colleagues' (2008) study is not surprising, as findings from recent meta-analytic (Kasper, Alderson, & Hudec, 2012; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005) and experimental (e.g., Tarle et al., 2017) studies suggest that central executive processes appear to be the most impaired component of working memory in children with ADHD.

Previous studies are also limited due to their uniform reliance on rating scales to measure emotion regulation, which are prone to be confounded by variance associated with behavioral disorders given the inherent overlap/similarity in questions targeting both constructs (e.g., *Does the child exhibit temper tantrums or irritability?*; Bunford, Evans, & Wymbs, 2015; Graziano & Garcia, 2016). While emotion regulation deficits associated with

ADHD and behavioral disorders share a similar phenotype, the etiology of behavioral disorders are typically due to inconsistent discipline and defiance rather than emotion regulation deficits (Bunford et al., 2015), whereas ADHD-related emotion regulation deficits may be due to executive function deficits. Ratings scales may also be inherently vulnerable to rater bias and error in retrospective recall of children's behavior, as Sjöwall and Thorell (2018) found that teacher reports on ratings scales, relative to laboratory-based measures, overestimate deficits of emotion regulation and other executive functions.

Observational/behavioral coding is a promising alternative approach that minimizes many limitations associated with rating scales by directly measuring real-time changes in children's emotion regulation behaviors (e.g., Adrian, Zeman, & Veits, 2011; Bunford et al., 2015; Zeman, Klimes-Dougan, Cassano, & Adrian, 2007). Relatively few studies of emotion regulation deficits in children with ADHD, however, have used observational coding in lieu of rating scales. Collectively, findings from these studies provide evidence that observational/behavioral coding methodology yields reliable and valid indices of emotion dysregulation that correlate with peers problems, maladaptive social behavior (Sjöwall & Thorell, 2018), chronic aggression and delinquency, and inattention (Hill, Degnan, Calkins, & Keane, 2006), and are predictive of social performance and knowledge of social status (Maedgen & Carlson, 2000; Melnick & Hinshaw, 2000).

A secondary benefit of observational/behavioral coding is the ability to observe real-time changes in behavior that covary with manipulated variables, which in turn establishes temporal precedence and allows for causal inferences. To that end, the current study combines observational coding with methodology derived from dual process theory of cognition (Barrett, Tugade, & Engle, 2004). Specifically, the dual process theory suggests that many neurocognitive processes are limited resources that are depleted with use, and other downstream neurocognitive processes associated with concurrent tasks are expected to evince performance declines due to a bottleneck of available resources (Baddeley, 2003; Rohrer & Pashler, 2003). Children who complete a high-demand working memory task, for example, are expected to have fewer available working memory resources that may be allocated to regulate emotions.

The current study is the first to examine hypothesized etiological features of ADHD-related emotion regulation deficits by incorporating dual-process theory and observational coding. Specifically, variability in emotion regulation was observed and coded across tasks that systematically increase working memory demands. Based on previous meta-analytic findings that identified large-magnitude emotion regulation (Graziano & Garcia, 2016) and working memory (Kasper et al., 2012) deficits, children with ADHD were expected to exhibit disproportionately greater emotion regulation deficits from low to high working memory conditions, compared to the TD children.

CHAPTER II

METHOD

Participants

Children between the ages of 8 and 12 years old were recruited from flyers posted around the community, communication with local organizations (e.g., boy or girl scouts; parent-teacher organizations), mass emails to faculty and staff at the university, and a university-based mental health clinic. Prior to study participation, parents and children provided written consent and assent, respectively. Parents of all participating children were provided with full psychoeducational reports from the evaluation that included several reliable and valid behavioral rating scales, cognitive and academic achievement assessments, behavioral observations, and clinical interviews.

Group Assignment. Children were assigned to the ADHD or TD groups based on a comprehensive diagnostic procedure that is consistent with the gold standard of identifying children with ADHD (Gualtieri & Johnson, 2005). Specifically, children and their parent(s)/guardian(s) completed an independently administered, semi-structured clinical interview, the Kiddie-Schedule for Affective Disorders and Schizophrenia-Present and Lifetime Version (K-SADS-PL; Kaufman et al., 1997, 2016). Children's parents and teachers also completed standardized rating scales including the Child

Behavior Checklist (CBCL; Achenbach & Rescorla, 2001), Teacher Report Form (TRF; Achenbach & Rescorla, 2001), and Conners-3 Parent and Teacher Ratings (C3P/T; Conners, 2008). Children were administered the K-SADS-PL, standardized self-report rating scales including the Children's Depression Inventory (CDI; Kovacs, 2003) and Revised Children's Manifest of Anxiety-2 (RCMAS-2; Reynolds & Richmond, 2008), a measure of cognitive functioning (i.e., Wechsler Scale of Intelligence for Children-IV (WISC-IV; Wechsler, 2003) or Wechsler Scale of Intelligence for Children-V (WISC-V; Wechsler, 2014)) and a measure of academic achievement (i.e., Kaufman Test of Educational Achievement-II (KTEA-II; Kaufman & Kaufman, 2004) or Kaufman Test of Educational Achievement-3 (KTEA-3; Kaufman & Kaufman, 2014)).

Children included in the ADHD group had: (1) a diagnosis of ADHD by the directing psychologist of the Center for Research of Attention and Behavior based on DSM-5 diagnostic criteria (APA, 2013), supported by information from the K-SADS-PL; (2) parent ratings that fell in the clinical range on DSM ADHD subscale on the CBCL or C3P; and (3) teacher ratings that fell in the clinical range on DSM ADHD subscale on the TRF or C3T. Of the 41 children who met inclusion criteria in the ADHD group, 28 were diagnosed with ADHD Combined Presentation and 13 were diagnosed with ADHD Predominantly Inattentive Presentation. Twenty-eight children with ADHD also met criteria for at least one comorbid disorder, including oppositional defiant disorder (n = 14), specific learning disorder (n = 8), enuresis (n = 4), encopresis (n = 2), disruptive mood dysregulation disorder (n = 2), conduct disorder (n = 1), specific phobia (n = 1), persistent depressive disorder (dysthymia; n = 1), or major depressive disorder (n = 1). This percentage of comorbidity is consistent with previous epidemiological studies

(Busch et al., 2002) that suggest children with ADHD are commonly diagnosed with co-occurring mood, anxiety, behavior, elimination, and learning disorders. All children were required to discontinue the use of medication 24 hours prior to all research sessions.

Children in the TD group had: (1) no clinical diagnosis based on the parent and child K-SADS-PL interviews and standardized rating scales (i.e., CBCL/TRF, C3P/T); and (2) normal developmental history based on information provided by the parent during a psychosocial interview. A total of 35 children were included in the TD group.

Children presenting with (1) gross neurological, sensory, or motor impairment, (2) psychosis, (3) a history of a seizure disorder, or (4) a WISC-IV or WISC-V Full Scale IQ (FSIQ) score less than 80 were excluded from the study. These factors may introduce confounds due to insufficient cognitive abilities to comprehend task instructions. Moreover, sensory or motor impairments may limit their ability to detect or respond to stimuli. Finally, some tasks require fast, repetitive stimuli presentations that may put children with a seizure disorder at-risk for having a seizure.

Measures

Phonological (PH) Working Memory Task. The PH task (Alderson et al., 2015) measured phonological working memory and was programmed using SuperLab Pro 4.5 software (Cedrus Corporation). The PH task presented a series of shuffled numbers (i.e., ranging from one to nine) and one letter (e.g., T, G, A, M) for each trial, similar to the WISC-V's Letter Number Sequencing task (Wechsler, 2014). However, the letter never appeared in the first or last position of the series, and stimuli were not presented twice in the same trial. The stimuli were delivered at a comfortable volume through computer speakers. A 200 ms inter-stimulus interval occurred after each number or letter was presented. Following each trial and stimulus presentation, an auditory click occurred before a green traffic light appeared on the screen prompting children to make a verbal response. Children were instructed to rearrange and say the numbers in order from least to greatest and then say the letter last. Following verbal responses, children touched a touch-screen computer monitor (37 x 30 cm screen) to advance to the next trial.

Children were allotted a maximum of 10,000 ms per stimulus to respond (e.g., 40,000 ms for set-size 4) before the next trial started. The PH task was split into four blocks of varying set-sizes that correspond to the number of stimuli (3, 4, 5, and 6), and each set-size block consisted of 24 consecutive trials. The set-sizes were presented in a counter-balanced order to control for potential order effects. Prior to task administration, a block of five practice trials were administered before set-size 3 and again before set-sizes 4, 5, or 6 (depending on the counter-balanced order). Children were required to obtain an 80% or higher success rate during practice trials before beginning the experimental trials. Verbal responses were independently recorded by two coders situated behind a one-way mirror. Coders' responses were compared for inter-rater agreement. When discrepancies occurred, the responses were verified using video and audio recordings to remediate the disagreement. The dependent variable for working memory performance was the mean number of stimuli recalled correctly during each set-size. The four means obtained from this procedure were then averaged to create a *PH composite* score.

Control Conditions. Children were instructed to draw or paint anything that they wanted for five minutes using the Microsoft Paint program. This condition places minimal demands on the temporary recall, rehearsal, or storage of information (i.e., working memory; Baddeley, 2007). Children completed two blocks of the control condition with one at the beginning (Control 1) and one at the end (Control 2) of each research session. This format allowed for the examination of potential fatigue effects and manipulation of working memory demands.

Emotion Regulation Coding. Adapted from previously established protocols (e.g., Melnick & Hinshaw, 2000), children's behavior was coded from videos of the children completing the PH task and control conditions using Noldus The Observer XT, version 8 (Noldus Information Technology, 2008). Emotion regulation behaviors that were coded included *Self-Praise/Positive Self-Task*, *Self-Criticism/Negative Self-Talk*, *Solicitations*, *Emotion Ventilation*, *Positive Emotion Expression*, *Shuts Down*, and *Total Emotion Expression* (see Table 1 for operational definitions and examples of each behavior). *Emotion Ventilation* was initially coded as Mild Emotion Ventilation and Intense Emotion Ventilation, but later combined due to the infrequency of intense emotion ventilation and moderate correlation ($r = 0.48$) between mild and intense emotion ventilation. Behaviors were required to occur for a minimum of one second to be coded, and behaviors were not mutually exclusive. For example, a child that expressed, "I am awful at this game" in a negative tone was coded as Self-Criticism/Negative Self-Talk and Emotion Ventilation.

Two of the study's lead researchers coded a complete set of behaviors and revised the coding definitions until 100% reliability was achieved. The coded video of behaviors was then used as a training video for other coders to practice and establish reliability. Each coder was required to reach at least 90% agreement with the lead researchers' videos for each task before proceeding to the coding of videos containing real data.

Twenty percent of videos were scored by two coders blind to children's diagnostic status to monitor reliability throughout the coding process. Disagreements were discussed with the lead researcher to yield scores used in subsequent analyses. The kappa values ranged from 0.90 to 1.00 for self-praise, self-criticism, shuts down, solicitations, and emotion ventilation, and the kappa values ranged from 0.85 to 1.00 for positive emotion expression. Two dependent variables were derived for each behavior. First, the duration of time children exhibited each behavior was divided by the duration of each task to yield the percentage of time the behavior was observed at each condition (i.e., at each control condition or PH task set-size). Next, a composite score was created for each behavior by averaging the percentage of time the behavior was observed across conditions (e.g., emotion ventilation at Control 1, PH3, PH4, PH5, PH6, and Control 2 were averaged to create an emotion ventilation composite).

Intellectual Functioning. Children's current level of intellectual functioning was assessed using the WISC-IV (n = 58) or WISC-V (n = 17), depending on the version that was current at the time of the assessment. The WISC-IV and WISC-V were used to determine group inclusion (FSIQ > 80) and rule-out the presence of an intellectual disability. Due to the strong association between working memory processes and FSIQ (Wechsler, 2003), controlling for FSIQ in subsequent analyses would remove variability associated with the study's independent variable. Consequently, following a procedure outlined by Alderson et al. (2010), and alternative estimate of FSIQ was created (i.e., *FSIQ residual*) to reflect FSIQ with variance associated with working memory removed. Specifically, a regression analysis was conducted with the PH composite as the independent variable and FSIQ as the dependent variable. The residual scores obtained from this procedure (i.e., *FSIQ residual*) reflected FSIQ without variance associated with working memory, and was used in subsequent analyses.

Standardized Rating Scales. Parents and teachers of the children completed broadband (i.e., CBCL/TRF) and narrow-band (i.e., C3P/C3T) rating scales as a measure of children's emotional and behavioral functioning. The DSM ADHD scales from the C3P, C3T, CBCL, and TRF were used to examine between-group effects in ADHD symptoms. The Conners-3 Global Index: Emotional Lability subscales from the C3P and C3T were averaged to create a *Conners-3 Emotional Lability Composite* score. The emotional lability composite score was utilized to examine the construct validity of the emotion regulation variables in Tier 2. Finally, children were administered the CDI and RCMAS-2 to measure depression-related and anxiety-related symptoms, respectively. CDI Total and RCMAS-2 Total *T*-scores were used as potential covariates in Tier 3.

Procedure

Behavioral rating scales were obtained from the parents and teachers prior to the first clinical session. Children completed the cognitive and achievement assessments during two, three-hour clinical sessions, while their parent(s) completed the psychosocial interview and semi-structured clinical interview (i.e., K-SADS-PL). Clinical sessions were scheduled during weekday mornings to minimize potential fatigue from school or extracurricular activities that may affect children's performance. After the clinical assessment was completed, children were administered the PH task and control conditions as part of a larger battery of experimental tasks that occurred during three, three-hour research sessions. Research sessions were scheduled on Saturday mornings and/or early afternoons to minimize the number of school absences. Frequent breaks were taken after every two to three tasks to help reduce fatigue. Children were also administered the self-report rating scales and clinical interview during research sessions. After completing the clinical and research sessions, parents were provided with a copy of a comprehensive psychoeducational report during a feedback session to explain the results of the child's assessment.

Data Analytic Plan

All analyses were conducted using Statistical Package for the Social Sciences (SPSS), Version 24 (IBM Corp., 2016). Tier 1 provided a preliminary examination of sample characteristics. Potential between-group differences in age, SES, FSIQ residual, and ethnicity were examined as a first step using independent samples *t*-tests (age, gender, SES, FSIQ residual) and Pearson's chi-square tests (ethnicity) to determine if covariate analyses were warranted. Additionally, independent samples *t*-tests examined between-group differences for ratings of emotional and behavioral functioning (CBCL, TRF, C3P, C3T, CDI, RCMAS-2). In Tier 2, Pearson's *r* correlations between coded emotion regulation composite scores and emotional lability composite were examined to evaluate construct validity of the emotion regulation codes, as many studies have highlighted the necessity for using multi-method assessments of emotion regulation to understand what aspects of the construct are being analyzed (Adrian, Zeman, & Veits, 2011; Zeman, Klimes-Dougan, Cassano, & Adrian, 2007). Further, correlations between emotion regulation composite scores, working memory performance, and self-reported internalizing symptoms were examined to determine if working memory performance and internalizing symptoms might serve as potential covariates in subsequent analyses. Specifically, internalizing symptoms of anxiety and depression were examined as potential covariates, since these disorders are also associated with emotion regulation deficits (e.g., Aldao, Nolen-Hoeksema, & Schweizer, 2010; Southam-Gerow & Kendall, 2001) that may confound ADHD-specific deficits. That is, children with ADHD are at increased risk for comorbid mood and anxiety disorders (e.g., Biederman et al., 1991) that may confound emotion regulation deficits associated with ADHD. Working memory performance was examined for the potential that children with ADHD would exhibit greater emotion regulation deficits due to poorer performance. This will examine if between-group differences in emotion regulation are due to increased working memory loads or perceived performance.

Seven, 2 (ADHD, TD) by 6 (Control 1, PH3, PH4, PH5, PH6, and Control 2) mixed-model analyses of variance (ANOVA) were used to examine the potential interaction effects between group and condition on emotion regulation deficits (i.e., total emotion expression and individual codes) for Tier 3. Significant interaction effects were probed using independent samples *t*-tests to examine between-group effects at each condition and repeated-measures ANOVAs to examine within within-group effects. Follow-up mixed-model analyses of covariance (ANCOVA) were performed to examine if significant effects remained after including covariates from Tier 2. Significant interaction effects were probed using univariate ANCOVAs to examine between-group effects and repeated-measures ANCOVAs to examine within-group effects. Main effects were interpreted for all non-significant interactions. Greenhouse-Geisser corrected degrees of freedom were reported when the Mauchly's Test of Sphericity was significant, suggesting the assumption of sphericity was violated.

CHAPTER III

RESULTS

Tier 1: Preliminary Analyses

Missing data. One ADHD participant's data was excluded from all analyses because their video did not contain audio. Seven participants ($n_{\mathrm{ADHD}} = 4$, $n_{\mathrm{TD}} = 3$) were also excluded due to having one control condition video that did not contain at least five minutes of video data. The final sample included 68 participants ($n_{\mathrm{ADHD}} = 36$, $n_{\mathrm{TD}} = 32$).

Power. G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) was used to determine the sample size needed to detect within-group, between-group, and interaction effects across planned analyses. To estimate the power needed, a Cohen's *d* effect size of 0.80 was used based on the magnitude of ADHD-related emotion regulation deficits reported in a recent meta-analysis (Graziano & Garcia, 2016). Power was set to 0.80 based on Cohen's (1988) recommendations. For an effect size of 0.80, $\alpha = .05$, power = 0.80, 2 groups and 6 conditions (4 PH set-sizes, 2 Controls), 10 total participants are needed for a mixed-model analysis of variance (ANOVA) to detect an interaction, within-group, and between-group effect. For a mixed-model ANCOVA with an effect size of 0.80, $\alpha = .05$, power = 0.80, numerator $df = 1$, 2 groups, and 2 covariates, a total sample size of 52 is suggested to detect significant main effects and interactions. The current study's final sample included 68 children, suggesting it was sufficiently powered.

Outliers. All variables were screened for univariate outliers prior to running analyses. Outliers were defined as values at least 3.29 standard deviations (corresponding with a *p*-value of .001) above or below the group's mean (Tabachnick & Fidell, 2001). Outliers were replaced with a value equal to ± 3.29 standard deviations from the mean, dependent on the direction of the outlier. Eleven total emotion expression ($n_{\text{ADHD}} = 5$, $n_{\text{TD}} = 6$), 15 self-criticism ($n_{\text{ADHD}} = 11$, $n_{\text{TD}} = 4$), 9 self-praise ($n_{\text{ADHD}} = 7$, $n_{\text{TD}} = 2$), 9 shuts down ($n_{\text{ADHD}} = 7$, $n_{\text{TD}} = 2$), 15 solicitations ($n_{\text{ADHD}} = 13$, $n_{\text{TD}} = 2$), 9 emotion ventilation ($n_{\text{ADHD}} = 5$, $n_{\text{TD}} = 4$), and 27 positive emotion expression ($n_{\text{ADHD}} = 22$, $n_{\text{TD}} = 5$) scores were identified as outliers.

Sample characteristics. The ADHD and TD groups did not differ based on gender ($t(66) = -0.48$, $p = .634$, $d = -0.12$), age ($t(66) = 0.60$, $p = .549$, $d = 0.15$), SES[1] ($t(65) = 1.74$, $p = .087$, $d = 0.43$), ethnicity ($\chi^2(4) = 2.21$, $p = .697$), or FSIQ residual[2] ($t(65) = 0.65$, $p = .519$, $d = 0.16$). As expected, children with ADHD had significantly higher ratings on all rating scales compared to the TD group (see Table 2).

Tier 2: Intercorrelations

The Conners-3 emotional lability composite was significantly, positively correlated with several observational codes, including the total emotion expression composite ($r = 0.39$, $p = .001$), solicitations composite ($r = 0.33$, $p = .007$), emotion

[1] Hollingshead SES scores were not available for three participants due to insufficient information (e.g., missing parental education data).
[2] One child was administered the Woodcock-Johnson Test of Cognitive Abilities-IV (Schrank, McGrew, & Mather, 2014), since the WISC-V was administered within the previous year. The score was not included in the between-group analysis.

ventilation composite ($r = 0.35$, $p = .004$), and positive emotion expression composite ($r = 0.34$, $p = .004$). Moreover, group status was significantly correlated with the Conners-3 emotional lability composite ($r = 0.56$, $p < .001$), total emotion expression composite ($r = 0.42$, $p < .001$), self-criticism composite ($r = 0.32$, $p = .007$), solicitations composite ($r = 0.25$, $p = .039$), emotion ventilation composite ($r = 0.32$, $p = .009$), and positive emotion expression composite ($r = 0.41$, $p < .001$). See Table 3 for a summary of emotion regulation behaviors and Conners-3 emotional lability ratings correlations.

Small to moderate correlations were observed among emotion regulation composite scores and the PH composite, as well as emotion regulation composite scores and CDI Total (see Table 3). RCMAS-2 Total, however, was not associated with any emotion regulation composite scores. Therefore, PH composite and CDI Total, but not RCMAS-2 Total, were used as covariates in Tier 3.

Tier 3: Examination of Emotion Regulation Deficits and Increased Demands on Working Memory

Total Emotion Expression. A 2 (ADHD, TD) by 6 (Control 1, PH3, PH4, PH5, PH6, and Control 2) mixed-model ANOVA examined the potential group by condition interaction effect on total emotion expression. The between-group main effect was significant, $F(1, 66) = 13.93$, $p < .001$, $\eta^2_{partial} = 0.17$, suggesting children with ADHD demonstrated significantly greater total emotion expression compared to TD peers. The interaction, $F(2.91, 192.05) = 1.60$, $p = .193$, $\eta^2_{partial} = 0.02$, and main effect for condition, $F(2.91, 192.05) = 2.13$, $p = .100$, $\eta^2_{partial} = 0.03$, were not significant (see Table 4 and Figure 1).

A 2 by 6 mixed-model ANCOVA examined a potential group by condition interaction on total emotion expression while controlling for PH composite and CDI Total. Children with ADHD expressed significantly more emotions compared to TD children ($F(1, 64) = 5.36$, $p = .024$, $\eta^2_{partial} = 0.08$). There was also a significant main effect for condition ($F(3.21, 205.19) = 9.68$, $p < .001$, $\eta^2_{partial} = 0.13$). Pairwise comparisons revealed greater total emotion expression during PH5 ($p = .003$), PH6 ($p = .006$), and Control 2 ($p = .031$) compared to PH3. Additionally, more frequent emotion expression was observed during PH5 ($p = .002$) and PH6 ($p = .004$) compared to PH4. The interaction effect was not significant, $F(3.21, 205.19) = 0.96$, $p = .417$, $\eta^2_{partial} = 0.02$ (see Table 5 and Figure 1).

Self-Criticism. There was a significant interaction between group and condition on self-criticism, $F(5, 330) = 2.53$, $p = .029$, $\eta^2_{partial} = 0.04$. The ADHD group exhibited significantly more self-criticism than the TD group at PH3, $t(38.76) = -2.03$, $p = .049$, $d = -0.46$, and PH6, $t(46.19) = -2.24$, $p = .030$, $d = -0.56$. The groups did not differ at Control 1 ($t(66) = -0.94$, $p = .350$, $d = -0.35$), PH4 ($t(31) = 1.00$, $p = .325$, $d = 0.49$), PH5 ($t(53.93) = -1.81$, $p = .076$, $d = -0.45$), and Control 2 ($t(66) = -0.94$, $p = .350$, $d = -0.35$). The main effect for condition was significant for the ADHD group ($F(5, 175) = 4.15$, $p = .001$, $\eta^2_{partial} = 0.11$), but not for the TD group ($F(5, 155) = 0.67$, $p = .645$, $\eta^2_{partial} = 0.02$). Post hoc pairwise comparisons for the ADHD group revealed significantly more self-criticism during PH3 ($p = .027$), PH5 ($p = .022$), and PH6 ($p = .015$) compared to Control 1. The ADHD group also had more frequent self-criticism during PH4 ($p = .026$) and Control 2 ($p = .027$) compared to PH3, and more frequent self-criticism during PH5 ($p = .007$) and PH6 ($p = .008$) compared to PH4. Finally, self-criticism scores were more frequent for the ADHD group during PH5 (p = .022) and PH6 (p = .015) compared to Control 2 (see Table 4 and Figure 2).

A mixed-model ANCOVA examined the group by condition interaction effect on self-criticism while controlling for PH composite and CDI Total. There was a significant main effect for condition, $F(5, 320) = 3.66$, $p = .003$, $\eta^2_{\text{partial}} = 0.05$. Pairwise comparisons indicated less self-criticism during Control 1 compared to PH3 (p = .019), PH5 (p = .007), and PH6 (p = .010). Further, less self-criticism was observed during PH4 compared to PH3 (p = .025), PH5 (p = .006), and PH6 (p = .008). Finally, self-criticism scores during Control 2 were less than PH3 (p = .019), PH5 (p = .007), and PH6 (p = .010). The interaction effect, $F(5, 320) = 1.49$, $p = .192$, $\eta^2_{\text{partial}} = 0.02$, and main effect for group, $F(1, 64) = 3.33$, $p = .073$, $\eta^2_{\text{partial}} = 0.05$, were not significant (see Table 5 and Figure 2).

Emotion Ventilation. There was a significant interaction between group and condition on emotion ventilation, $F(3.01, 198.68) = 3.09$, $p = .028$, $\eta^2_{\text{partial}} = 0.05$. The ADHD group exhibited significantly more frequent emotion ventilation compared to the TD group during PH4 ($t(57.02) = -2.03$, $p = .048$, $d = -0.49$), PH6 ($t(37.18) = -3.20$, $p = .003$, $d = -0.74$), and Control 2 ($t(49.45) = -2.27$, $p = .028$, $d = -0.52$). Post hoc, repeated-measures ANOVAs revealed significant within-group main effects for the TD group, $F(1.37, 42.47) = 5.01$, $p = .021$, $\eta^2_{\text{partial}} = 0.14$, and ADHD group, $F(2.93, 102.61) = 6.34$, $p = .001$, $\eta^2_{\text{partial}} = 0.15$. Pairwise comparisons for the TD group indicated emotion ventilation during Control 1 was significantly less than PH5 (p = .019) and PH6 (p = .003), and scores during Control 2 were significantly less than PH4 (p = .047), PH5 (p = .014), and PH6 (p = .002). Additionally, emotion ventilation was significantly more frequent during PH5 compared to PH3 (p = .026). Pairwise comparisons for the ADHD group revealed more frequent emotion ventilation during PH6 compared to Control 1 (p < .001), PH3 (p = .021), PH4 (p = .002), and Control 2 (p = .001). Further, emotion ventilation during PH5 were significantly more frequent than Control 1 (p = .015) and Control 2 (p = .008), and emotion ventilation during PH4 was significantly more frequent than Control 2 (p = .008; see Table 4 and Figure 3).

A mixed-model ANCOVA revealed the interaction effect (F(2.90, 185.50) = 1.75, p = .161, $\eta^2_{partial}$ = 0.03), within-group main effect (F(2.90, 185.50) = 1.45, p = .230, $\eta^2_{partial}$ = 0.02), and between-group main effect (F(1, 64) = 1.78, p = .187, $\eta^2_{partial}$ = 0.03) were not significant after controlling for PH composite and CDI Total (see Table 5 and Figure 3).

Positive Emotion Expression. The interaction between group and condition on positive emotion expression was significant, F(2.11, 139.03) = 8.20, p < .001, $\eta^2_{partial}$ = 0.11. The ADHD group exhibited significantly more positive emotion expression compared to the TD group during Control 1 (t(35.55) = -2.35, p = .024, d = -0.55) and Control 2 (t(35.57) = -4.07, p < .001, d = -0.95). The groups were not significantly different during PH3 (t(63.20) = -1.91, p = .061, d = -0.56), PH4 (t(66) = -1.20, p = .236, d = -0.29), PH5 (t(66) = -0.96, p = .340, d = -0.24), and PH6 (t(59.23) = -1.94, p = .058, d = -0.47). The within-group effect was significant for the ADHD group, F(2.04, 71.51) = 8.90, p < .001, $\eta^2_{partial}$ = 0.20, but not for the TD group, F(2.33, 72.18) = 0.92, p = .415, $\eta^2_{partial}$ = 0.03. Pairwise comparisons for the ADHD group revealed positive emotion expression during Control 2 was significantly greater than Control 1 (p = .039), PH3 (p = .001), PH4 (p = .001), PH5 (p < .001), and PH6 (p < .001; see Table 4 and Figure 4).

A mixed-model ANCOVA revealed a significant group by condition interaction effect after statistically controlling for PH composite and CDI Total, $F(2.11, 135.22) = 3.57$, $p = .029$, $\eta^2_{partial} = 0.05$. The ADHD group exhibited more positive emotion expression compared to the TD group at Control 2, $F(1, 64) = 6.46$, $p = .013$, $\eta^2_{partial} = 0.09$. The groups did not significantly differ at Control 1 ($F(1, 64) = 1.97$, $p = .165$ $\eta^2_{partial} = 0.03$), PH3 ($F(1, 64) = 1.74$, $p = .192$, $\eta^2_{partial} = 0.03$), PH4 ($F(1, 64) = 0.70$, $p = .404$, $\eta^2_{partial} = 0.01$), PH5 ($F(1, 64) = 0.09$, $p = .765$, $\eta^2_{partial} = 0.00$), or PH6 ($F(1, 64) = 2.65$, $p = .109$, $\eta^2_{partial} = 0.04$). There were not significant within-group effects for the TD group, $F(2.28, 66.02) = 1.12$, $p = .352$, $\eta^2_{partial} = 0.04$, or ADHD group, $F(2.04, 67.28) = 1.41$, $p = .222$, $\eta^2_{partial} = 0.04$ (see Table 5 and Figure 3).

Self-Praise. The interaction effect, $F(2.82, 186.32) = 0.88$, $p = .447$, $\eta^2_{partial} = 0.01$, between-group main effect, $F(1, 66) = 0.48$, $p = .492$, $\eta^2_{partial} = 0.01$, and main effect for condition, $F(2.82, 186.32) = 0.66$, $p = 0.566$, $\eta^2_{partial} = 0.01$, were not significant (see Table 4 and Figure 5). A mixed-model ANCOVA revealed the interaction effect, $F(2.81, 179.49) = 0.53$, $p = .650$, $\eta^2_{partial} = 0.01$, and between-group main effect, $F(1, 64) = 1.42$, $p = .238$, $\eta^2_{partial} = 0.02$, were not significant after controlling for PH composite and CDI Total. The main effect for condition was significant, $F(2.81, 179.49) = 3.14$, $p = .029$, $\eta^2_{partial} = 0.05$, however, but the pairwise comparisons did not reveal any significant differences between conditions (see Table 5).

Shuts Down. There was a significant main effect for condition, $F(5, 330) = 3.59$, $p = .004$, $\eta^2_{partial} = 0.05$. Pairwise comparisons revealed more frequent shutting down during PH5 compared to Control 1 ($p = .026$), PH3 ($p = .026$), and Control 2 ($p = .026$). The interaction effect, $F(5, 330) = 2.04$, $p = .073$, $\eta^2_{partial} = 0.03$, and between-group main effect, $F(1, 66) = 3.28$, $p = .075$, $\eta^2_{partial} = 0.05$, were not significant (see Table 4 and Figure 6).

A mixed-model ANCOVA was performed to examine potential interaction effects when controlling for PH composite and CDI Total. There was a significant within-group effect, $F(5, 320) = 7.17$, $p < .001$, $\eta^2_{partial} = 0.10$. Pairwise comparisons revealed more frequent shutting down during PH5 compared to Control 1 ($p = .017$), PH3 ($p = .017$), PH4 ($p = .040$), and Control 2 ($p = .017$). The interaction effect ($F(5, 320) = 0.98$, $p = .433$, $\eta^2_{partial} = 0.02$) and main effect for group ($F(1, 64) = 1.58$, $p = .213$, $\eta^2_{partial} = 0.02$) were not significant (see Table 5 and Figure 6).

Solicitation. The ADHD group, compared to the TD group, exhibited more frequent solicitations with a significant between-group main effect, $F(1, 66) = 4.42$, $p = .039$, $\eta^2_{partial} = 0.06$. The within-group main effect was also significant, $F(1.96, 129.43) = 4.51$, $p = .013$, $\eta^2_{partial} = 0.06$. Pairwise comparisons indicated more frequent solicitations occurred during PH6 compared to Control 1 ($p = .012$), PH3 ($p = .010$), and PH4 ($p = .020$). Additionally, more frequent solicitations occurred during PH5 compared to Control 1 ($p = .022$) and PH3 ($p = .010$). Finally, the interaction effect was not significant, $F(1.96, 129.43) = 1.50$, $p = .228$, $\eta^2_{partial} = 0.02$ (see Table 4 and Figure 7). After controlling for PH composite and CDI Total, there was not a significant interaction effect ($F(1.89, 120.81) = 0.37$, $p = .681$, $\eta^2_{partial} = 0.01$), between-group main effect ($F(1.89, 120.81) = 2.98$, $p = .057$, $\eta^2_{partial} = 0.05$), or within-group main effect ($F(1, 64) = 0.45$, $p = .506$, $\eta^2_{partial} = 0.01$). See Table 5 and Figure 7 for a summary.

CHAPTER IV

DISCUSSION

Findings from previous studies (Berlin et al., 2004; Sjöwall et al., 2013, 2015; Wåhlstedt et al., 2008) have been relatively equivocal with regard to the relationship between ADHD-related working memory and emotion regulation deficits. These studies have relied on measures that place few demands on the central executive component of working memory (i.e., forward and backward span tasks provide metrics of simple storage/rehearsal processes; Moleiro et al., 2013), and consequently do not tax working memory processes most impaired in children with ADHD (e.g., Kasper et al., 2012). Further, previous studies have uniformly relied on emotion regulation rating scales that are likely to be confounded with comorbid disorders or global impairments (e.g., Bunford et al., 2015), and at best, yield correlational findings that do not allow for causal inferences. The current study is the first to examine the functional relationship between varying working memory demands and changes in behaviorally-coded emotion regulation exhibited by children with and without ADHD.

Correlations were examined as a first step. Children's composite emotional lability scored derived from the Conners-3 rating scales was moderately associated with the majority of composite behavioral codes including total emotion expression, solicitations, emotion ventilation, and positive emotion expression. Although these correlations appear to provide evidence of construct validity with respect to the study's operational definitions, it is worth noting that the magnitude of the correlations is smaller than expected, and a minority of the correlations (e.g., shuts down, self-criticism, self-praise) were not significant. One potential explanation for the non-significant correlations is that, although emotional lability and emotion regulation are moderately to strongly correlated (e.g., Derryberry & Rothbart, 1988; Eisenberg et al., 1993), they are distinct constructs such that emotional lability typically refers to a frequent onset and/or rapid changes in emotions (Cole et al., 1994; Graziano & Garcia, 2016), whereas emotion regulation refers to a broader range of processes that include self-regulating emotions' expressions, intensity, and duration to obtain a goal (Thompson, 1994, 2011). Alternatively, the non-significant correlations may simply reflect excessive error variance/noise derived from correlating scores derived from different methodological approaches (i.e., correlating ratings scale data with behavioral observations). Previous research comparing rating scale and laboratory metrics of selective attention, for example, suggest that parent and teacher ratings of inattention and hyperactivity evince low to moderate ecological validity compared to laboratory-based metrics (e.g., Barkley, 1991). Sources for variability in scores across methodological procedures might include: the broad array of settings (e.g., home, work, leisure time) in which ratings scales might be completed, compared to highly structured laboratories where behaviors are observed and recorded; ratings scales' requirement that parents/teachers retrospectively recall children's behaviors, compared to behavioral observations that collect data immediately in real time or via observations of recordings; and subjective interpretations of rating scale items, compared to operationally defined overt behaviors that are coded.

Overall, children with ADHD, compared to TD children, exhibited large-magnitude, between-group total emotion expression differences which aligns with findings from previous meta-analytic (Graziano & Garcia, 2016) and experimental (e.g., Banaschewski et al., 2012; Braaten & Rosén, 2000; Musser et al., 2011; Rosen & Factor, 2012) studies. The primary aim of the current study, however, was to examine if ADHD-related emotion regulation deficits are functionally related to varying demands on working memory. A priori, it was hypothesized that children with ADHD, compared to typically developing children, would exhibit a disproportionate increase in emotional dysregulation as working memory demands increased, and this disproportionate increase in emotional dysregulation would provide evidence for a causal relationship between ADHD-related working memory and emotion regulation deficits. Rationale for this hypothesis was derived from basic cognitive (Baddeley, 2003; Cowan, 2010) and social (e.g., Schmeichel et al., 2008; Schmeichel & Demaree, 2010) research that suggests working memory and self-regulation are limited resources that deplete with use. If working memory is involved in emotional regulation, one would expect increased emotional dysregulation during high working memory conditions due to fewer available resources (e.g., Baddeley, 2003). Moreover, relative to TD children, children with ADHD would be expected to exhibit disproportionate increases in emotion dysregulation due to large-magnitude impairments in working memory that are characteristic of the disorder (Kasper et al., 2012; Rapport et al., 2008). Indeed, as predicted, the current findings indicate that children in the ADHD group exhibited a disproportionate increase in self-criticism and emotion ventilation during the high working memory conditions. Collectively, these findings align with predictions from Rapport et al.'s (2008) functional working memory model of ADHD that suggests working memory deficits underlie secondary deficits of the disorder, including affected children's ability to regulate negative emotions and/or implement coping strategies, and add to a growing body of literature that suggests working memory underlies ADHD-related hyperactivity (Rapport et al., 2009), impulsivity (Patros et al., 2017), inattention (Kofler et al., 2010), disinhibition (e.g., Alderson et al., 2010; Tarle et al., under review), and social problems (Kofler et al., 2011).

Children with ADHD, compared to TD children, exhibited a disproportionate increase in positive emotion expression during low working memory demand conditions. To some degree, these findings appear to provide convergent validity for the a priori hypothesis that emotion regulation deficits, and particularly increased negative emotions, would be greatest during conditions of high working memory demands. It is noted, however, that the disproportionately greater frequency of positive emotion expressions during control conditions might also reflect a deficit (e.g., Braaten & Rosén, 2000; Bunford et al., 2015; Maedgen & Carlson, 2000). For example, excessive laughing, singing, and/or celebrating may decrease controlled-focused attention, increase off-task behavior, and/or serve as a distraction to other children in a classroom setting. Further, emotion regulation has been examined as a factor to distinguish between different psychological disorders (e.g., Southam-Gerow & Kendall, 2001), and the dysregulation of positive emotions appears to be unique to ADHD-related emotion regulation (Faraone et al., 2018). An increase in positive emotions among children with ADHD may be due to elevated parasympathetic activity during conditions that induce positive emotions and overall greater levels of arousal across all conditions (e.g., Musser et al., 2011).

Self-praise behaviors reflect a unique subset of positive emotion expressions that are distinct due to their egocentric characteristic (i.e., positive expressions about oneself). Surprisingly, self-praise behaviors did not differ between groups and did not significantly vary across conditions. These non-significant findings appear to contrast previous research that suggest children with ADHD exhibit a positive illusory bias—the inflation of self-perception in comparison to actual performance (e.g., Hoza et al., 2004). The discrepancy between our findings and extant literature may be explained by the use of observational methods in the current study, and open-ended questions and/or ratings scales in previous studies (e.g., Hoza et al., 2004; Hoza, Pelham, Waschbusch, Kipp, & Owens, 2001). Specifically, in contrast to the current study that observed and coded self-praise behaviors during working memory tasks, previous studies of illusory bias in children with ADHD typically solicit children's attitudes and feelings about their performance a priori or post-hoc of task completion (e.g., Hoza et al., 2001; Owens, Goldfine, Evangelista, Hoza, & Kaiser, 2007). The discrepancy in findings from the current study and past studies may provide evidence for construct error in previous studies that examine positive illusory bias due to poor metrics of the construct (e.g., Owens et al., 2007). Another potential explanation is that children with ADHD's increased self-perceptions of their performance is due to deficient error monitoring (e.g., Geburek, Rist, Gedeiga, Stroux, & Pedersen, 2013), which would result in a reification issue.

Children with ADHD exhibited moderately more solicitations compared to TD children. This finding contrasts previous research that suggest children with ADHD do not exhibit greater numbers of solicitations in a classroom setting (Abikoff et al., 2002) or during a frustration task (Melnick & Hinshaw, 2000). Further, children in both groups were more likely to exhibit solicitations and shuts down during conditions with greater working memory demands compared to conditions with lower working memory demands. This finding appears to reflect expected increases in solicitations and disengagement of children during more difficult and unstimulating tasks (Scime & Norvilitis, 2006). Moreover, the shutting down behavior may be related to learned helplessness (e.g., Overmier, 2002), withdrawn behavior (e.g., Ladd, 2006), and/or avoidance behaviors (e.g., Huijding et al., 2009), which have been linked with decreased test performance (e.g., Firmin, Hwang, Copella, & Clark, 2004), academic expectations (Valås, 2001), and psychological adjustment (Eisenberg et al., 1994; Ladd, 2006; Valås, 2001).

Lastly, all analyses were completed a second time with depression symptoms and working memory performance included as covariates to determine if the observed effects were due to potential confounds with internalizing symptoms (e.g., Aldao et al., 2010; Southam-Gerow & Kendall, 2001) and working memory performance (Kasper et al., 2012). Interestingly, the group by condition interaction effect for positive emotion expression remained significant after including covariates. This finding provides strong evidence that ADHD -related deficits in expressing positive emotions is not better accounted for by variability in depression symptoms or working memory performance. Moreover, within-group effects strengthened for total emotion expression, shuts down, self-praise, and total emotion expression, and did not change for self-criticism. These findings were not surprising, as previous research has indicated the inclusion of covariates in analyses can increase power (e.g., Borm, Fransen, & Lemmens, 2007; Hansen, 1995), which may explain the increased magnitude of the within-group effects. Finally, no significant effects for emotion ventilation or solicitations were found after controlling for depression and working memory performance. One potential explanation for this finding is that solicitations are similar in function to excessive reassurance seeking that has been identified in children at-risk (e.g., Joiner & Metalsky, 2001) or diagnosed (e.g., Joiner, Metalsky, Gencoz, & Gencoz, 2001) with clinical depression. Controlling for depressed mood, therefore, may have removed variability associated with topographically similar constructs (i.e., solicitations and reassurance seeking; Anastopoulos et al., 2011).

While the current study provides a unique examination of ADHD-related emotion regulation deficits when experimentally manipulating working memory, a few potential limitations warrant consideration. First, the ADHD group included children with comorbid disorders (e.g., oppositional defiant disorder, specific learning disorders, elimination disorders) that may have confounded the current study's estimates of ADHD-related emotion regulation deficits and working memory, since previous studies indicate executive function deficits are associated with other psychopathology (e.g., Pennington & Ozonoff, 1996). This rate of comorbidity, however, is expected based on past epidemiological findings (Busch et al., 2002), suggesting the inclusion of comorbid disorders in the sample is likely to increase generalizability of the current study to the general population of children with ADHD. Further, the current study examined potential covariates and statistically controlled for depression symptoms. The relatively low percentage of girls in the current study is another potential limitation that warrants future research to strengthen the generalizability of the current findings. The current study only measured emotion regulation deficits during a PH working memory task. Future research is needed to determine if these findings will generalize to other modalities (e.g., visuospatial) of working memory and other executive functions (e.g., self-control). Finally, behavioral observations of emotion regulation deficits are limited in that only external behaviors can be coded, and children may have internalized some processes that are not included in the current study. Therefore, future studies incorporating multiple measures of emotion regulation may help to generalize these experiences to multiple settings and situations.

Collectively, findings from this study suggest that variability in working memory demands are functionally related to the expression of disproportionate positive and negative emotions exhibited by children with ADHD, compared to TD peers. This study expands upon previous literature that suggests working memory deficits underlie the ADHD phenotype and its associated deficits, including emotion regulation (e.g., Rapport et al., 2008). These findings have relevant translational value with respect to understanding specific emotion regulation deficits exhibited by children with ADHD, and how variation in task- (e.g., homework vs video games), environment- (school vs play), and social- (formal vs friends) related neurocognitive demands are functionally related to their changes in emotional expression. Further, Faraone and colleagues (2018) recently commented that ADHD diagnostic criteria describes impulsivity within the context of behaviors and cognitions, but not emotions. Although this may be due to a number of factors including poor diagnostic metrics of emotion regulation, further knowledge of ADHD-related emotion regulation deficits and their etiology will assist with progressing the field's approaches to potential treatment directions and improving differential diagnostic accuracy. For example, developing emotion regulation strategies that lessen the burden on working memory processes may improve affected children's ability to regulate emotions successfully and decrease the associated impairment. Lastly, the development of assessment techniques to identify ADHD-related emotion dysregulation, such as a behavioral coding system, may assist with distinguishing these behaviors from comorbid disorders and minimizing the potential for over-diagnosis.

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TABLES AND FIGURES

Table 1. Emotion regulation observational codes.

Emotion Regulation Code	**Description of Code**	**Examples**
Emotion Ventilation	Displays negative emotion through vocal or gestural medium, such as grunting, making a gesture of disappointment	Sighing, shaking their head, verbally acknowledging his/her frustration, phrases said in negative tones, postural changes (e.g., slumping down), slamming fists, yelling, or whining loudly
Positive Emotion Expression	Displays positive, not neutral, emotional expression	Speaking in a positive tone, laughing, singing, or celebrating
Self-Criticism/ Negative Self-Talk	Any verbalizations directed negatively towards the self, his/her performance, or his/her mistakes	"I stink at this." "This is so hard." "Dang it. I got that wrong."
Self-Praise/ Positive Self-Talk	Any verbalizations directed positively towards oneself or his/her performance, such as positive affirmation or encouragement	"I can do this!" "I'm good at this." "I got that one right!"
Shuts Down	Disengages from the task demands, such as collapsing his/her body or crossing his/her arms and refusing to participate	Collapsing his/her body or crossing his/her arms and refusing to participate
Solicitations	Any verbal comment, including questions and complaints, directed towards the examiner	"Can I stop now?"
Total Emotion Expression	The total duration of all emotion regulation variables that were observed above while accounting for overlapping codes.	-

Note. Emotion regulation codes were not mutually exclusive. Emotion ventilation was coded as mild emotion ventilation and intense emotion ventilation, but these variables were combined due to low occurrence of intense emotion ventilation.

Table 2. Sample Characteristics, Rating Scale, and Composite Score Summary

	TD (*n* = 32)	**ADHD (*n* = 36)**			
	M (SD)	*M (SD)*	χ^2	*t*	*d*
Sample Characteristics					
Ethnic Composition			2.21		
Caucasian	78%	81%			
Native American	3%	8%			
Hispanic	3%	3%			
Asian	3%	0%			
Biracial	13%	8%			
Gender (percent female)	13%	17%		-0.48	-0.12
Age	10.04 (1.46)	9.81 (1.69)		0.60	0.15
SES	50.41 (10.82)	46.09 (9.56)		1.74	0.43
FSIQ residual	0.85 (10.80)	-0.73 (9.25)		0.65	0.16
Rating Scales					
CBCL DSM-ADHD	53.69 (5.11)	67.64 (6.90)		-9.54***	-2.31
TRF DSM-ADHD	53.63 (5.63)	64.44 (6.84)		-7.07***	-1.74
C3P DSM-ADHD-I	51.19 (11.17)	76.58 (9.93)		-9.93***	-2.45
C3P DSM-ADHD-HI	52.63 (13.35)	70.58 (15.15)		-5.16***	-1.27
C3T DSM-ADHD-I	49.13 (8.07)	73.56 (8.65)		-12.00***	-2.96
C3T DSM-ADHD-HI	52.34 (15.51)	66.67 (16.72)		-3.65**	-0.89
RCMAS-2	40.31 (8.14)	46.33 (9.99)		-2.70**	-0.67
CDI	43.94 (6.63)	50.03 (10.83)		-2.75**	-0.68

Note. ADHD = Attention-deficit/hyperactivity disorder; TD = Typically developing; SES = Hollingshead socioeconmic status scores; FSIQ residual = Full Scale IQ score controlling for working memory performance; CBCL = Child Behavior Checklist; TRF = Teacher Report Form; C3P = Conners-3 Parent Rating Scale; C3T = Conners-3 Teacher Rating Scale; DSM-ADHD = Attention-deficit/hyperactivity problems scale; DSM-ADHD-I = DSM ADHD inattention subscale; DSM-ADHD-HI = DSM ADHD hyperactive/impulsive subscale; RCMAS-2 = Revised Children's Manifest for Anxiety Symptoms Total Score; CDI = Children's Depression Inventory Total Score; *d* = Cohen's *d* effect size.
**p* < .05, ***p* < .01, ****p* < .001

Table 3. Correlations of covariate, emotion regulation, and emotional lability variables.

	TD	**ADHD**													
	***M* (*SD*)**	***M* (*SD*)**	***d***	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**	**9.**	**10.**	**11.**	**12.**
1. Group				1.00											
2. WM Perf.	3.39 (0.73)	2.75 (0.81)	0.84	-0.39**	1.00										
3. Depression	43.94 (6.63)	50.03 (10.83)	-0.68	0.32**	-0.23	1.00									
4. Anxiety	40.31 (8.14)	46.33 (9.99)	-0.67	0.32**	-0.16	0.53***	1.00								
5. EL	48.44 (6.55)	62.82 (13.35)	-1.37	0.56***	-0.19	0.35**	0.33**	1.00							
6. Total EE	1.05 (1.35)	5.68 (6.90)	-0.92	0.42***	-0.33**	0.34**	-0.01	0.39**	1.00						
7. Self-Criticism	0.01 (0.02)	0.05 (0.07)	-0.77	0.32**	-0.23	0.24*	0.08	0.13	0.36**	1.00					
8. Self-Praise	0.00 (0.01)	0.00 (0.01)	-0.00	0.09	0.16	0.04	-0.07	0.17	0.10	0.14	1.00				
9. Shuts Down	0.05 (0.21)	0.50 (1.38)	-0.45	0.22	-0.34**	-0.09	-0.15	0.14	0.50***	0.24	0.00	1.00			
10. Solicitation	0.01 (0.05)	0.05 (0.10)	-0.50	0.25*	-0.33**	0.30*	0.21	0.33**	0.29*	0.35**	0.01	0.14	1.00		
11. Emo. Vent.	0.63 (0.83)	1.71 (2.12)	-0.67	0.32**	-0.24*	0.43***	0.08	0.35**	0.78***	0.37**	0.13	0.02	0.27*	1.00	
12. Pos. EE	0.30 (0.64)	1.75 (2.14)	-0.91	0.41**	-0.27*	0.35**	0.05	0.34**	0.80***	0.24*	0.11	0.05	0.35**	0.71**	1.00

Note. Summary of means, standard deviations, effect sizes, and Pearson's *r* correlations for the emotion regulation variables, emotional lability ratings, working memory performance, and internalizing symptoms. Group = Diagnostic grouping; Emotional Lability = Conners-3 Parent and Teacher Emotional Lability composite; Total EE = Composite of total emotion expression scores; Self-Criticism = Self-criticism/negative self-talk composite; Self-Praise = Self-praise/positive self-talk composite; Shuts Down = Shuts down composite; Solicitations = Composite of solicitation scores; Emo. Vent. = Composite of emotion ventilation scores; Pos. EE = Composite of positive emotion expression scores; TD = Typically developing; ADHD = Attention-deficit/hyperactivity disorder.
*$p < .05$, **$p < .01$, ***$p < .001$

Table 4. Summary of ANOVA Results

	TD	ADHD				
	M (SD)	*M (SD)*	*F*	*t*	*d*	LSD Post hoc
Total Emotion Expression						
Control 1	0.33 (0.61)	5.24 (14.60)	-	-	-0.47	
PH3	0.69 (1.18)	3.08 (4.87)	-	-	-0.67	
PH4	1.09 (1.86)	3.86 (7.65)	-	-	-0.49	
PH5	2.73 (4.54)	6.61 (10.50)	-	-	-0.48	
PH6	1.05 (1.71)	8.00 (11.29)	-	-	-0.85	
Control 2	0.38 (0.76)	7.28 (11.46)	-	-	-0.84	
Between-Group			13.93^{***}			
Within-Group			2.13			
Group x WM			1.60			
Self-Criticism/Negative Self-Talk						
Control 1	0.00 (0.00)	0.01 (0.04)	-	-0.94	-0.35	
PH3	0.01 (0.05)	0.09 (0.24)	-	-2.03^{*}	-0.46	
PH4	0.01 (0.03)	0.00 (0.00)	-	1.00	0.49	
PH5	0.02 (0.07)	0.07 (0.14)	-	-1.81	-0.45	
PH6	0.01 (0.08)	0.10 (0.21)	-	-2.24^{*}	-0.56	
Control 2	0.00 (0.00)	0.01 (0.04)	-	-0.94	-0.35	
Between-Group			7.76^{**}			
Within-Group			4.19^{**}			PH3,PH5,PH6> C1,PH4,C2
Group x WM			2.53^{*}			
ADHD Post hoc			4.15^{**}			PH3,PH5,PH6> C2,PH4,C2
TD Post hoc			0.67			
Emotion Ventilation						
Control 1	0.17 (0.42)	0.66 (1.84)	-	-1.55	-0.36	
PH3	0.40 (0.65)	1.56 (3.63)	-	-1.88	-0.44	
PH4	0.59 (1.23)	1.44 (2.13)	-	-2.03^{*}	-0.49	
PH5	1.79 (3.60)	2.39 (3.98)	-	-0.65	-0.16	
PH6	0.72 (0.95)	3.78 (5.66)	-	-3.20^{**}	-0.74	
Control 2	0.14 (0.34)	0.45 (0.76)	-	-2.27^{**}	-0.52	
Between-Group			7.31^{**}			
Within-Group			8.17^{***}			C1,C2<PH3,PH4 ,PH5,PH6; PH4<PH5; PH6>PH3,PH4
Group x WM			3.09^{*}			
ADHD Post hoc			6.34^{**}			C1<PH5; PH6>C1,PH3,

TD Post hoc			5.01^{*}			PH4,C2; C2<PH4,PH5 C1<PH5,PH6; PH3<PH5; C2<PH4,PH5, PH6
Positive Emotion Expression						
Control 1	0.19 (0.48)	2.45 (5.73)	-	-2.35^{*}	-0.55	
PH3	0.28 (0.10)	0.84 (1.39)	-	-1.91	-0.56	
PH4	0.47 (1.06)	0.81 (1.27)	-	-1.20	-0.29	
PH5	0.40 (1.20)	0.69 (1.30)	-	-0.96	-0.24	
PH6	0.23 (0.68)	0.66 (1.11)	-	-1.94	-0.47	
Control 2	0.22 (0.60)	5.03 (7.06)	-	-4.07^{***}	-0.95	
Between-Group			13.59^{***}			
Within-Group			7.17^{**}			C2>C1,PH3,PH4 ,PH5,PH6
Group x WM			8.20^{***}			
ADHD Post hoc			8.90^{***}			C2>C1,PH3,PH4 ,PH5,PH6
TD Post hoc			0.92			
Self-Praise/Positive Self-Talk						
Control 1	0.00 (0.00)	0.00 (0.00)	-	-	0.00	
PH3	0.00 (0.00)	0.01 (0.03)	-	-	-0.47	
PH4	0.01 (0.03)	0.01 (0.03)	-	-	0.00	
PH5	0.00 (0.00)	0.00 (0.01)	-	-	0.00	
PH6	0.01 (0.04)	0.00 (0.01)	-	-	0.36	
Control 2	0.00 (0.00)	0.01 (0.03)	-	-	-0.47	
Between-Group			0.48			
Within-Group			0.66			
Group x WM			0.88			
Shuts Down						
Control 1	0.00 (0.00)	0.00 (0.00)	-	-	0.00	
PH3	0.00 (0.00)	0.00 (0.00)	-	-	0.00	
PH4	0.00 (0.00)	0.41 (2.07)	-	-	-0.28	
PH5	0.33 (1.28)	1.41 (4.13)	-	-	-0.35	
PH6	0.00 (0.00)	1.19 (3.63)	-	-	-0.46	
Control 2	0.00 (0.00)	0.00 (0.00)	-	-	0.00	
Between-Group			3.28			
Within-Group			3.59^{**}			PH5>C1,PH3,C2
Group x WM			2.04			
Solicitations						
Control 1	0.00 (0.00)	0.01 (0.04)	-	-	-0.35	

PH3	0.00 (0.00)	0.00 (0.00)	-	-	0.00	
PH4	0.01 (0.08)	0.04 (0.12)	-	-	-0.30	
PH5	0.00 (0.00)	0.08 (0.17)	-	-	-0.66	
PH6	0.05 (0.23)	0.13 (0.32)	-	-	-0.29	
Control 2	0.00 (0.00)	0.05 (0.16)	-	-	-0.44	
Between-Group			4.42^{*}			
Within-Group			4.51^{*}			PH5>C1,PH3; PH6>C1,PH3, PH4
Group x WM			1.50			

Note. TD = Typically developing; ADHD = Attention-deficit/hyperactivity disorder; *d* = Cohen's *d* effect size; LSD Post hoc = Least significant difference post hoc test; PH3 = Phonological task set-size 3; PH4 = Phonological task set-size 4; PH5 = Phonological task set-size 5; PH6 = Phonological task set-size 6; C1 = Control 1; C2 = Control 2.

Table 5. Summary of ANCOVAs with working memory performance and depression covariates

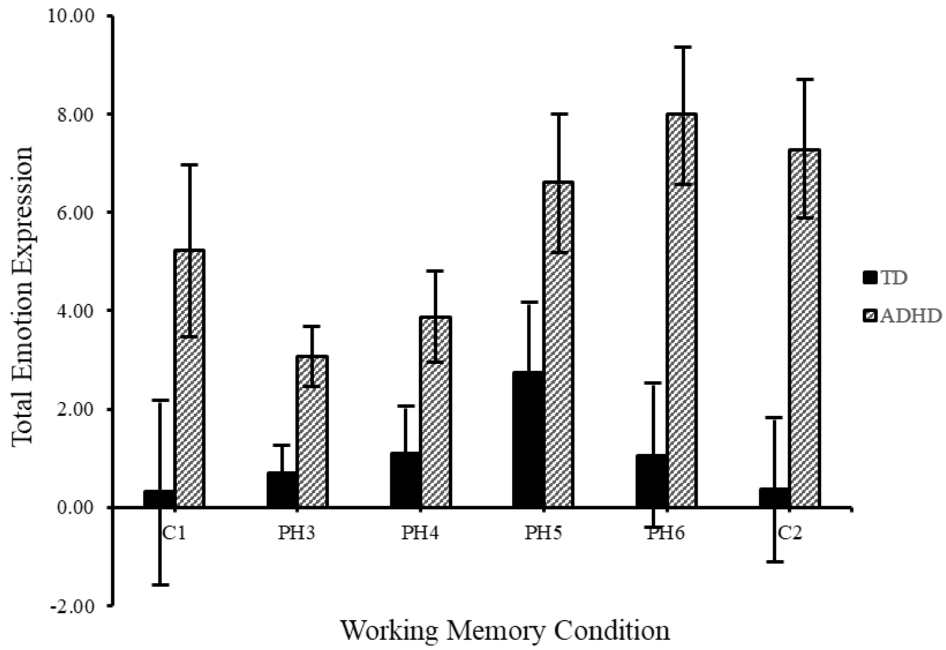
	TD	ADHD			
	M (SD)	*M (SD)*	*F*	*d*	LSD Post hoc
Total Emotion Expression					
Control 1	1.29 (10.42)	4.39 (10.35)	-	-0.30	
PH3	1.13 (3.79)	2.69 (3.76)	-	-0.42	
PH4	1.60 (6.06)	3.41 (6.02)	-	-0.30	
PH5	3.68 (8.39)	5.77 (8.34)	-	-0.25	
PH6	1.80 (8.75)	7.33 (8.69)	-	-0.64	
Control 2	1.57 (8.59)	6.23 (8.54)	-	-0.55	
Between-Group			5.36*		
Within-Group			9.68***		PH3<PH5,PH6,C2; PH4<PH5,PH6
Group x WM			0.96		
Self-Criticism/Negative Self-Talk					
Control 1	0.00 (0.03)	0.00 (0.03)	-	0.00	
PH3	0.03 (0.19)	0.08 (0.19)	-	-0.27	
PH4	0.01 (0.02)	-0.00 (0.02)	-	0.51	
PH5	0.01 (0.12)	0.07 (0.12)	-	-0.51	
PH6	0.03 (0.17)	0.09 (0.17)	-	-0.36	
Control 2	0.00 (0.03)	0.00 (0.03)	-	0.00	
Between-Group			3.33		
Within-Group			3.66**		PH3,PH5,PH6>C1,PH4,C2
Group x WM			1.49		
Emotion Ventilation					
Control 1	0.29 (1.26)	0.55 (1.25)	-	-0.21	
PH3	0.74 (2.77)	1.27 (2.75)	-	-0.20	
PH4	0.87 (1.81)	1.19 (1.80)	-	-0.18	
PH5	2.22 (4.01)	2.01 (3.98)	-	0.05	
PH6	1.16 (4.37)	3.39 (4.34)	-	-0.52	
Control 2	0.18 (0.64)	0.42 (0.64)	-	-0.38	
Between-Group			1.78		
Within-Group			1.45		
Group x WM			1.75		
Positive Emotion Expression					
Control 1	0.57 (4.28)	2.11 (4.25)	1.97	-0.37	
PH3	0.34 (1.31)	0.78 (1.31)	1.74	-0.34	
PH4	0.51 (1.27)	0.78 (1.26)	0.70	-0.22	
PH5	0.50 (1.33)	0.60 (1.32)	0.09	-0.08	
PH6	0.24 (0.99)	0.65 (0.98)	2.65	-0.42	

Control 2	0.92 (5.37)	4.41 (5.34)	6.45*	-0.66	
Between-Group			5.89*		
Within-Group			2.28		
Group x WM			3.57*		
ADHD Post hoc			1.41		
TD Post hoc			1.12		
Control 1	0.00 (0.03)	0.01 (0.03)	-	-0.34	
PH3	0.00 (0.00)	0.00 (0.00)	-	0.00	
PH4	0.03 (0.11)	0.03 (0.11)	-	0.00	
PH5	0.02 (0.13)	0.07 (0.13)	-	-0.39	
PH6	0.09 (0.29)	0.10 (0.29)	-	-0.04	
Control 2	0.01 (0.11)	0.04 (0.11)	-	-0.28	
Self-Praise/Positive Self-Talk					
Control 1	0.00 (0.00)	0.00 (0.00)	-	0.00	
PH3	0.00 (0.02)	0.01 (0.02)	-	-0.51	
PH4	0.00 (0.03)	0.01 (0.03)	-	-0.34	
PH5	0.00 (0.01)	0.00 (0.01)	-	0.00	
PH6	0.00 (0.03)	0.00 (0.03)	-	0.00	
Control 2	0.00 (0.02)	0.01 (0.02)	-	-0.51	
Between-Group			1.42		
Within-Group			3.14*		C1=PH3=PH4=PH5=PH6=C2
Group x WM			0.53		
Shuts Down					
Control 1	0.00 (0.00)	0.00 (0.00)	-	0.00	
PH3	0.00 (0.00)	0.00 (0.00)	-	0.00	
PH4	0.06 (1.61)	0.36 (1.60)	-	-0.19	
PH5	0.51 (3.15)	1.24 (3.13)	-	-0.24	
PH6	0.12 (2.74)	1.08 (2.73)	-	-0.36	
Control 2	0.00 (0.00)	0.00 (0.00)	-	0.00	
Between-Group			1.58		
Within-Group			7.17***		PH5>C1,PH3,PH4,C2
Group x WM			0.98		
Solicitations					
Control 1	0.00 (0.03)	0.01 (0.03)	-	-0.34	
PH3	0.00 (0.00)	0.00 (0.00)	-	0.00	
PH4	0.03 (0.11)	0.03 (0.11)	-	0.00	
PH5	0.02 (0.13)	0.07 (0.13)	-	-0.39	
PH6	0.09 (0.29)	0.10 (0.29)	-	-0.04	
Control 2	0.01 (0.11)	0.04 (0.11)	-	-0.28	
Between-Group			0.45		
Within-Group			2.98		

Group x WM	0.37

Note. TD = Typically developing; ADHD = Attention-deficit/hyperactivity disorder; *d* = Cohen's *d* effect size; LSD Post hoc = Least significant difference post hoc test; PH3 = Phonological task set-size 3; PH4 = Phonological task set-size 4; PH5 = Phonological task set-size 5; PH6 = Phonological task set-size 6; C1 = Control 1; C2 = Control 2.

(a.)



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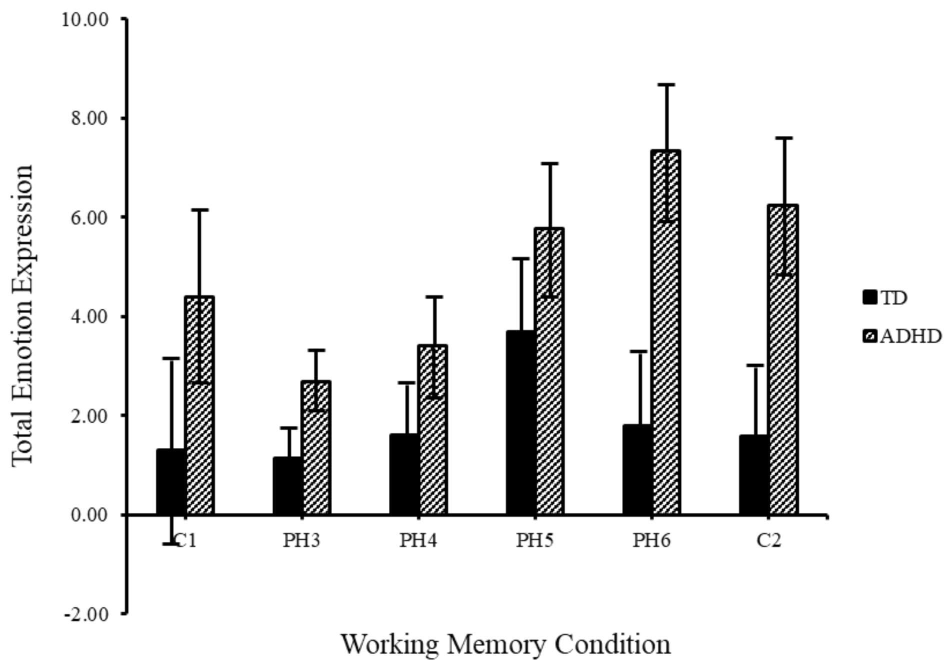
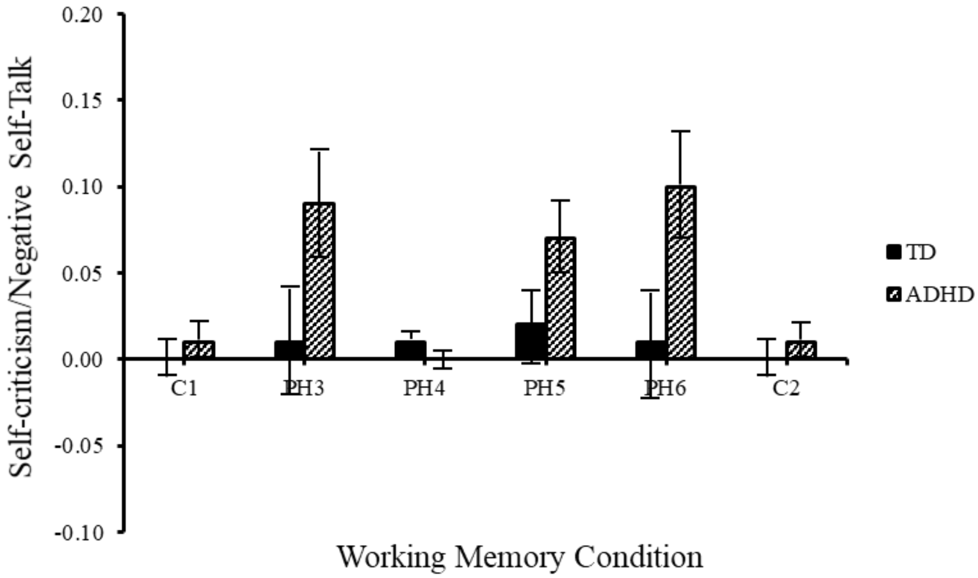


Figure 1. Visual schematic of group by working memory condition on total emotion expression for the (a) mixed-model ANOVA and (b) mixed-model ANCOVA with working memory performance and depression symptoms covariates. Error bars represent standard errors. C1 = Control 1; PH3 = Phonological task set-size 3; PH4 = Phonological task set-size 4; PH5 = Phonological task set-size 5; PH6 = Phonological task set-size 6; C2 = Control 2; TD = Typically developing; ADHD = Attention-deficit/hyperactivity disorder.

(a.)



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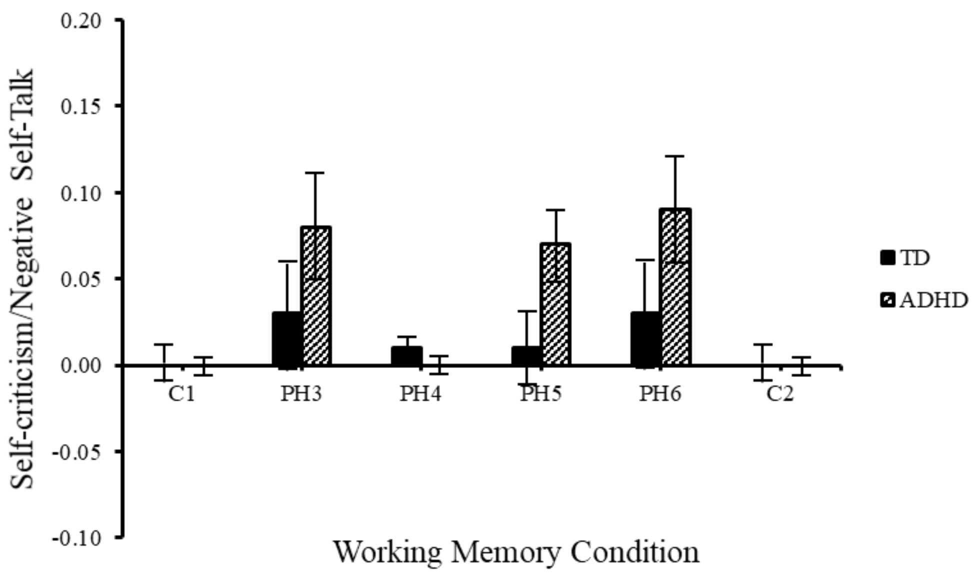
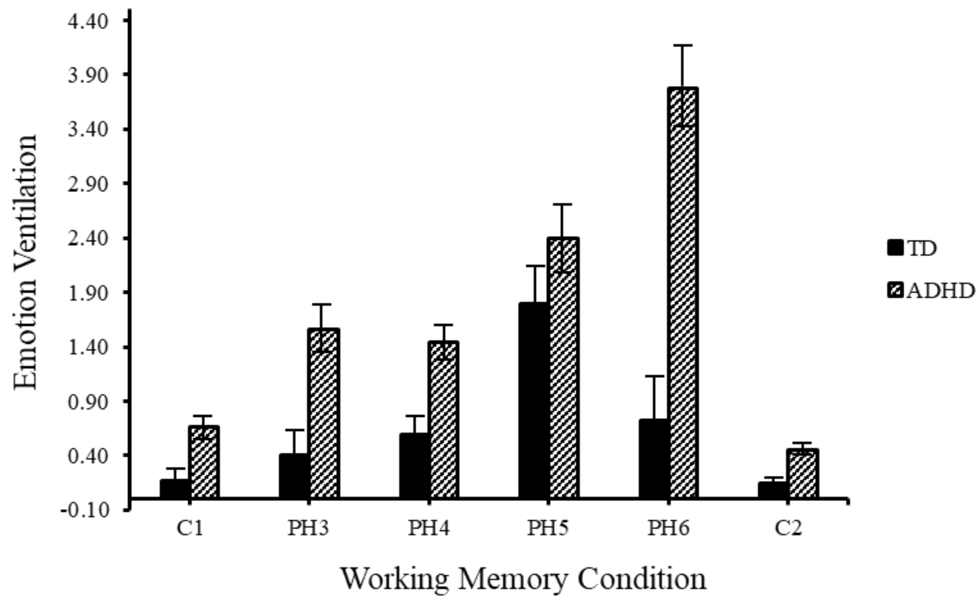


Figure 2. Visual schematic of group by working memory condition on self-criticism/negative self-talk for the (a) mixed-model ANOVA and (b) mixed-model ANCOVA with working memory performance and depression symptoms covariates. Error bars represent standard errors. C1 = Control 1; PH3 = Phonological task set-size 3; PH4 = Phonological task set-size 4; PH5 = Phonological task set-size 5; PH6 = Phonological task set-size 6; C2 = Control 2; TD = Typically developing; ADHD = Attention-deficit/hyperactivity disorder.

(a.)



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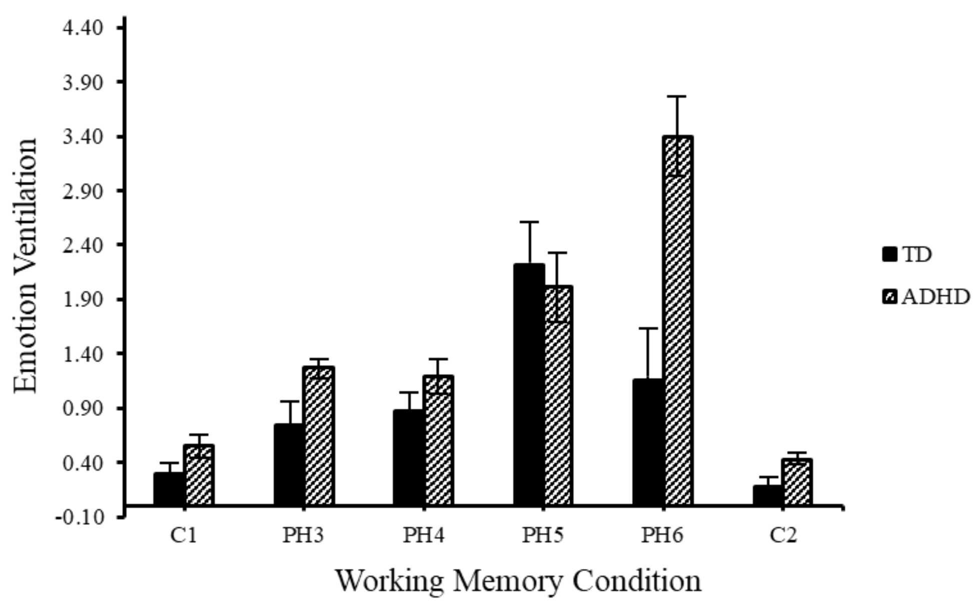
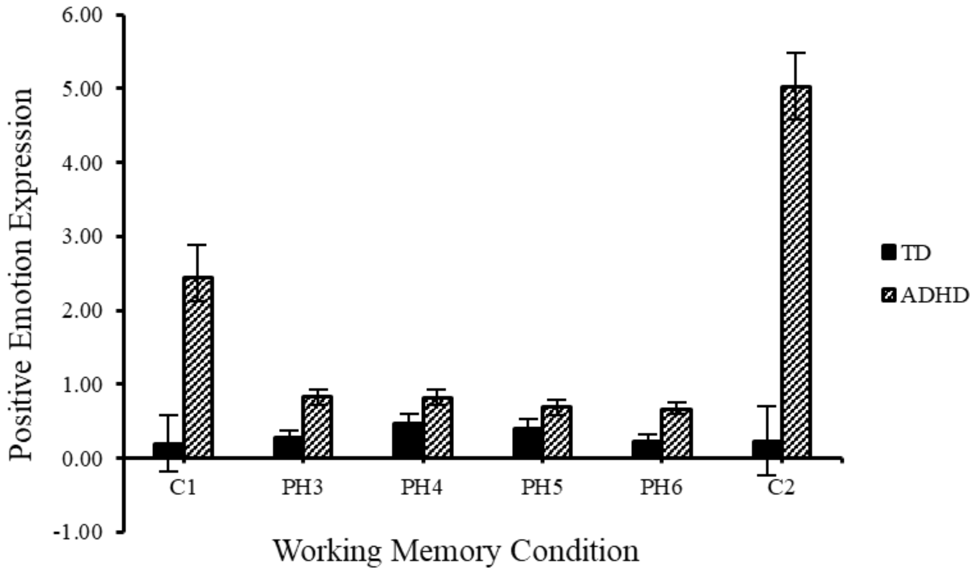


Figure 3. Visual schematic of group by working memory condition on emotion ventilation for the (a) mixed-model ANOVA and (b) mixed-model ANCOVA with working memory performance and depression symptoms covariates. Error bars represent standard errors. C1 = Control 1; PH3 = Phonological task set-size 3; PH4 = Phonological task set-size 4; PH5 = Phonological task set-size 5; PH6 = Phonological task set-size 6; C2 = Control 2; TD = Typically developing; ADHD = Attention-deficit/hyperactivity disorder.

(a.)



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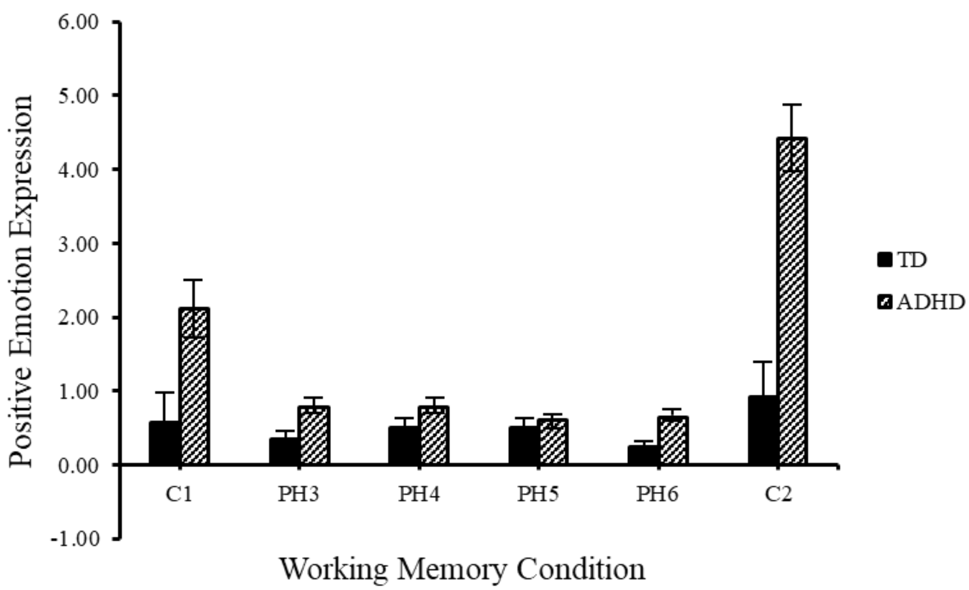
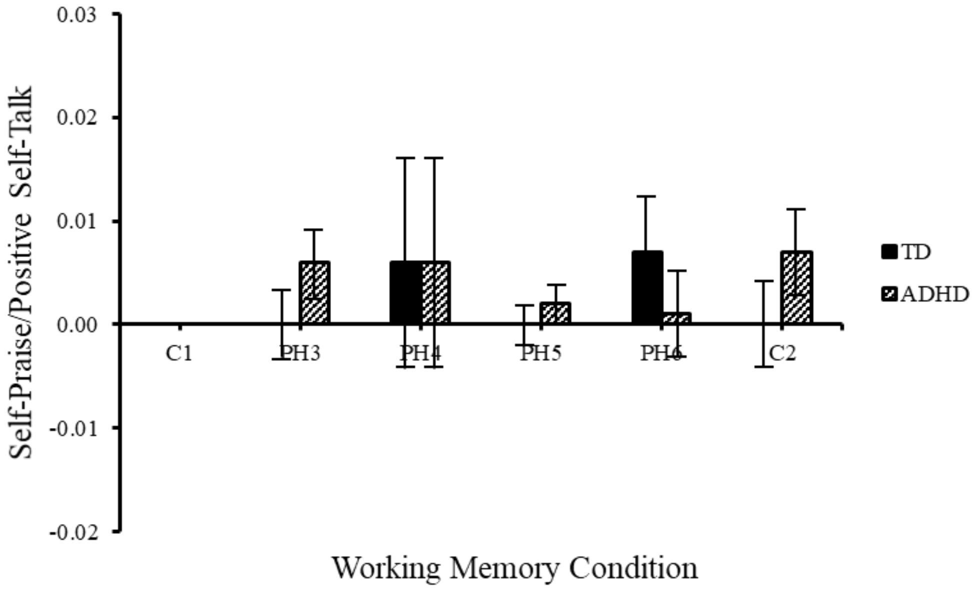


Figure 4. Visual schematic of group by working memory condition on positive emotion expression for the (a) mixed-model ANOVA and (b) mixed-model ANCOVA with working memory performance and depression symptoms covariates. Error bars represent standard errors. C1 = Control 1; PH3 = Phonological task set-size 3; PH4 = Phonological task set-size 4; PH5 = Phonological task set-size 5; PH6 = Phonological task set-size 6; C2 = Control 2; TD = Typically developing; ADHD = Attention-deficit/hyperactivity disorder.

(a.)



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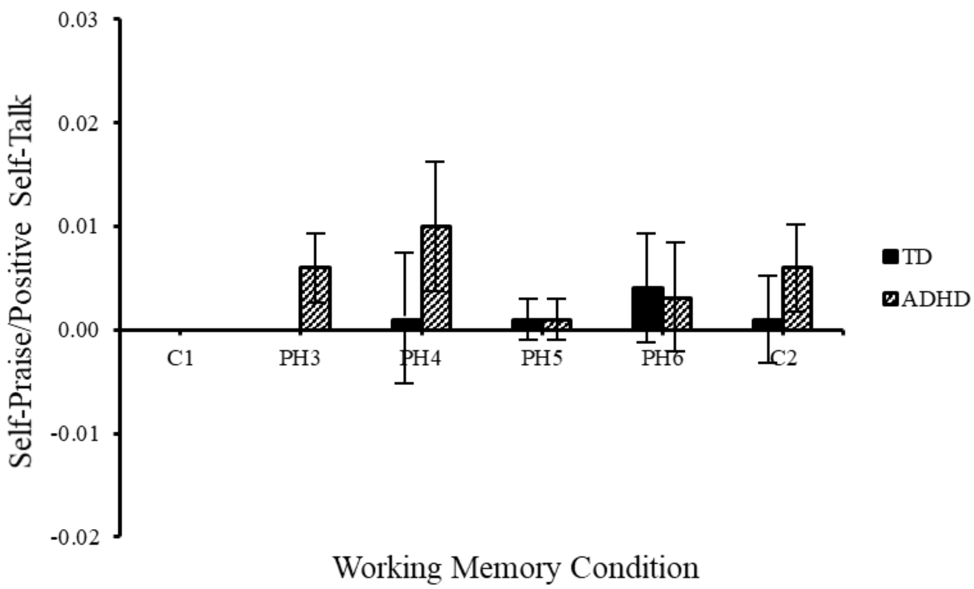
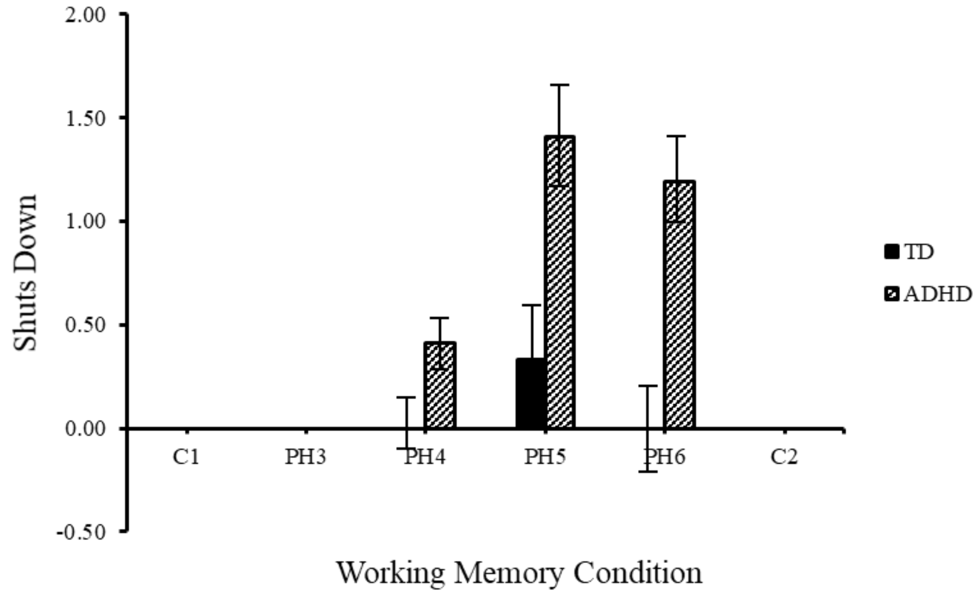


Figure 5. Visual schematic of group by working memory condition on self-praise/positive self-talk for the (a) mixed-model ANOVA and (b) mixed-model ANCOVA with working memory performance and depression symptoms covariates. Error bars represent standard errors. C1 = Control 1; PH3 = Phonological task set-size 3; PH4 = Phonological task set-size 4; PH5 = Phonological task set-size 5; PH6 = Phonological task set-size 6; C2 = Control 2; TD = Typically developing; ADHD = Attention-deficit/hyperactivity disorder.

(a.)



(b.)

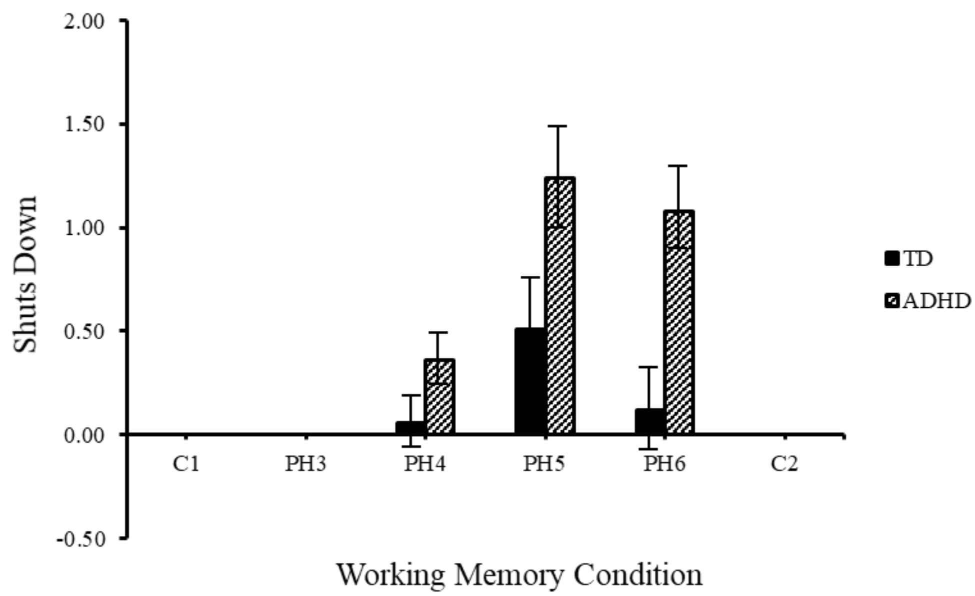
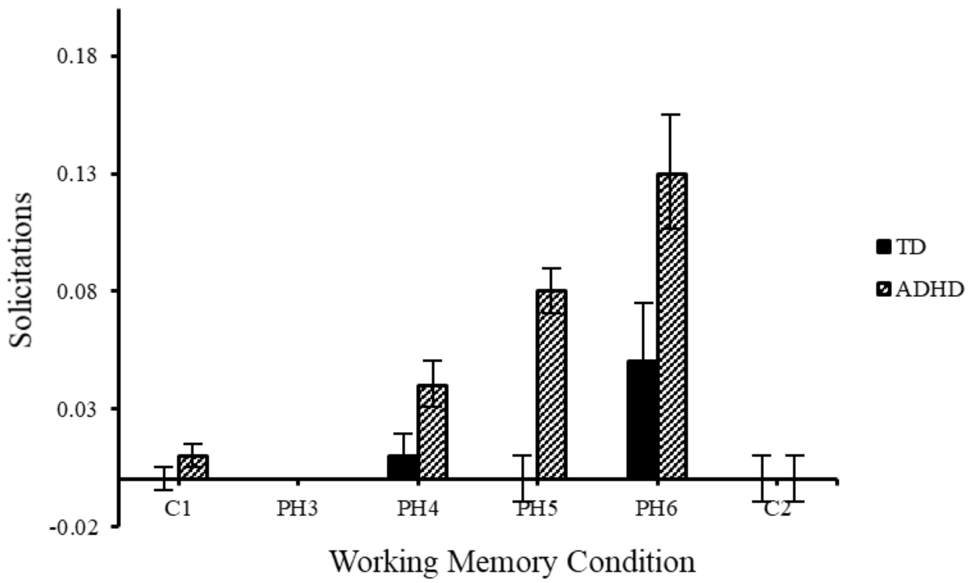


Figure 6. Visual schematic of group by working memory condition on shuts down for the (a) mixed-model ANOVA and (b) mixed-model ANCOVA with working memory performance and depression symptoms covariates. Error bars represent standard errors. C1 = Control 1; PH3 = Phonological task set-size 3; PH4 = Phonological task set-size 4; PH5 = Phonological task set-size 5; PH6 = Phonological task set-size 6; C2 = Control 2; TD = Typically developing; ADHD = Attention-deficit/hyperactivity disorder.

(a.)



(b.)

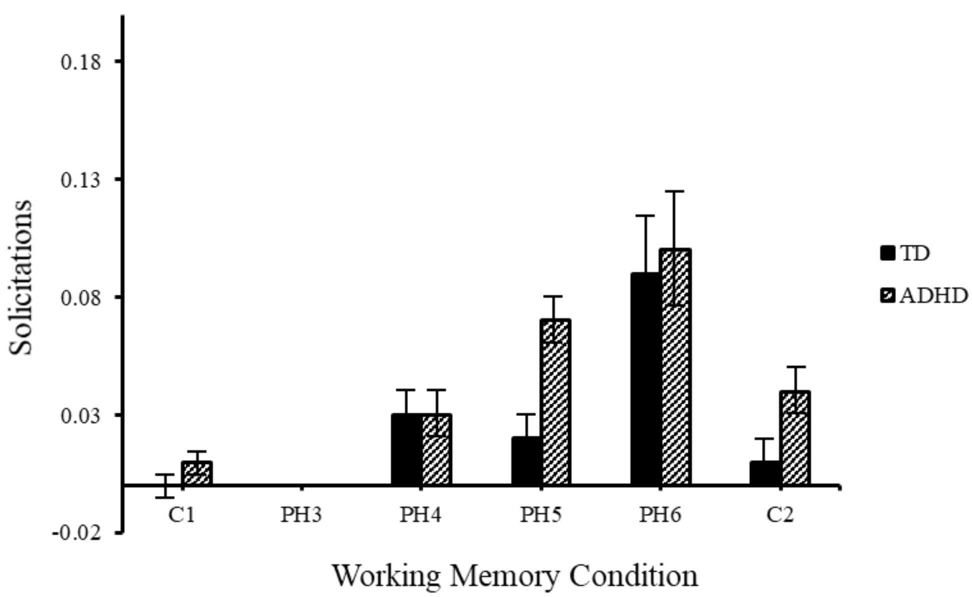


Figure 7. Visual schematic of group by working memory condition on solicitations for the (a) mixed-model ANOVA and (b) mixed-model ANCOVA with working memory performance and depression symptoms covariates. Error bars represent standard errors. C1 = Control 1; PH3 = Phonological task set-size 3; PH4 = Phonological task set-size 4; PH5 = Phonological task set-size 5; PH6 = Phonological task set-size 6; C2 = Control 2; TD = Typically developing; ADHD = Attention-deficit/hyperactivity disorder.

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