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Executive Functioning and Activity in Children: A Multimethod Examination of Working Memory, Inhibition, and Hyperactivity

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Abstract

Two primary methods of quantifying executive functioning include self- or other-reports (i.e., questionnaire-based EF) and cognitive test performance (i.e., task-based EF). Despite their lack of concordance with one another and relatively inconsistent associations with attention-deficit/hyperactivity disorder (ADHD) symptoms, both approaches have been utilized in attempts to advance our understanding of the role of EF in symptoms of ADHD. The current study is the first to incorporate a direct assessment of behavior (i.e., actigraphy) to further clarify the relation between EF and hyperactivity using a multi-method approach in a sample of children with a range of ADHD symptoms. Fifty-two children between the ages of 8 and 12 completed a testing session during which performance on working memory and inhibition computerized tasks, as well as actigraphy data, were collected. Additionally, parent reports of hyperactivity/impulsivity, working memory, and inhibition were obtained. As expected, questionnaire-based measures of working memory and inhibition were strongly associated with parent-reported hyperactivity/impulsivity, whereas only the latter was associated significantly with mechanically assessed movement. In contrast, task-based working memory performance was more strongly associated with parent-reported hyperactivity/impulsivity relative to task-based inhibition. Further, both task-based working memory and task-based inhibition were similarly associated with mechanically-assessed movement. Finally, compared to questionnaire-based EF, both measures of task-based EF accounted for more variance in objectively-assessed movement. Collectively, these results highlight the measurement issues in the present literature, the importance of careful task and questionnaire design, and the value that alternative approaches (e.g., actigraphy) may provide with respect to advancing our understanding of EF.

Keywords

Executive Functioning; Hyperactivity; Working Memory; Inhibition

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Attention-deficit/hyperactivity disorder (ADHD) is the most prevalent mental health concern of childhood (Doshi et al., 2012) and is associated with a wide range of impairments across multiple domains such as social functioning and academic performance (Garner et al., 2013). The disorder's prevalence, persistence, and associated adverse outcomes underscore the need to better understand the mechanisms underlying primary and secondary outcomes in ADHD. One mechanism that has been examined extensively in the ADHD literature is executive functioning (Alderson, Rapport, Kasper, Sarver, & Kofler, 2012; Krieger & Amador-Campos, 2018; Toplak, Bucciarelli, Jain, & Tannock, 2008), a broad construct referring to higher-order cognitive processes necessary for successful execution of goal-oriented behavior (Crippa et al., 2015; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Specifically, certain facets of executive functioning (EF) such as behavioral inhibition (Barkley, 1997) and working memory (e.g., Rapport, Chung, Shore, & Isaacs, 2001) have been of foremost interest as they are consistently impaired in ADHD (e.g., Snyder et al., 2015) and have been shown, experimentally and theoretically, to be important to our understanding of the disorder's symptoms such as hyperactivity (e.g., Barkley 1997; Puiu et al., 2018; Rapport, Bolden, Kofler, Raiker, & Alderson, 2009). Despite the exponential growth of the literature on executive functions (EFs) and the prominence of EFs as potentially core etiological processes in ADHD, substantial questions persist regarding its optimal measurement.

Two primary methods for studying EF include: 1) self- or informant-reported (e.g., parent) perceptions of the use of EFs across a variety of everyday activities (i.e., questionnaire-based EF), and 2) estimation of EF based on neurocognitive or neuropsychological test performance (i.e., task-based EF; Krieger & Amador-Campos, 2018; Toplak, West, & Stanovich, 2013). The literature on questionnaire-based EF reveals that children with ADHD are perceived by others to exhibit weaker EF than their typically developing peers on scales such as the Behavior Rating Inventory of Executive Functioning (BRIEF; Gioia, Guy, Isquith, & Kenworthy, 1996; Davidson, Cherry, & Corkum, 2016). Similarly, the literature on task-based EF indicates that children diagnosed with ADHD perform more poorly than their typically developing peers across multiple measures of EF including response inhibition, vigilance, spatial working memory, and planning (Pievsky & McGrath, 2018). Despite the fact that both task- and questionnaire-based EF are hypothesized to measure the same underlying constructs and both measures reveal consistent patterns of impairment in ADHD, the association between them ranges from absent to weak at best (Krieger & Amador-Campos, 2018; Mahone et al., 2002; Eycke & Dewey, 2016; Toplak et al., 2013; McAuley, Chen, Goos, Schachar, & Crosbie, 2010). For example, recent meta-analytic evidence (Toplak et al., 2013) reveals that less than one fifth of over 300 possible correlations between the BRIEF and various measures of task-based executive functioning are statistically significant. While there is some variability in correlation estimates[1], the majority of the literature suggests that these two methods of quantifying EF are weakly associated (average $r = 0.15$; Toplak et al., 2013).

The discrepancy between questionnaire-based and task-based EF raises significant questions regarding the extent to which information derived from each respective methodology improves our overall understanding of symptoms associated with ADHD. To date, work examining the association between EFs and hyperactivity/impulsivity has resulted in mixed findings. For example, parent and teacher reports of EF are consistently and highly associated with ratings of ADHD symptom severity such as hyperactivity/impulsivity, while task-based EFs are generally weakly associated (e.g., Krieger & Amador-Campos, 2018; Toplak et al., 2008). Initially, this work resulted in potentially premature conclusions that questionnaire-based EF measures (e.g., the BRIEF) have superior external validity and clinical utility (Lange et al., 2014; Tan, Delgaty, Steward, & Bunner, 2018) relative to task-based EF. However, recent evidence (Toplak et al., 2013; Eycke & Dewey, 2016) indicates that these two methods are likely measuring different aspects of the EF construct or potentially different constructs altogether. Indeed, a number of unresolved measurement issues may account for the discrepant pattern of relations between questionnaire-based and task-based assessment of EFs and parent report of symptoms. Specifically, the stronger association between questionnaire-based EFs and parent-reported ADHD symptoms reflects - to some extent - shared method variance, mono-informant biases, the relative timescale of behavior being reported on (e.g., sampling over several minutes with task-based EF versus sampling over the past several weeks or months with questionnaire-based EF), and item similarity among the measures (Barkley & Fischer, 2011; Bünger, Urger-Maurer, & Grob, 2019; Davidson et al., 2015; Krieger & Amador-Campos, 2018; McAuley et al., 2010; Silver 2014; Eycke & Dewey, 2016; Toplak et al., 2013; Vogt & Shameli, 2011). In order to advance the discrepant literature on EFs in ADHD, studies incorporating multiple methods of assessing symptoms in the same sample of youth simultaneously are necessary to disentangle the extent to which shared method variance is contributing to these associations.

In an effort to overcome some of the challenges outlined above, recent work has begun to incorporate other methods of quantifying symptoms that do not share the same measurement concerns (i.e., do not rely on other's reports). In particular, actigraphy has been used extensively to provide a more precise and direct index of overall activity level in children. Meta-analytic evidence supports the utility of actigraphy, revealing that those with ADHD consistently exhibit greater objectively-measured activity relative to those without the disorder (e.g., Alderson et al., 2012; Kofler, Raiker, Sarver, Wells, & Soto, 2016). Further, actigraphy has been found to differentiate ADHD and comparison groups (Matier-Sharma, Perachio, Newcorn, Sharma, & Halperin, 1995) and the association between parent-reported hyperactivity/impulsivity and movement quantified via actigraph is moderate ($r = 0.32$ to 0.58; Rapport et al., 2009).

In contrast to the aforementioned low associations between task-based EFs and parent ratings of ADHD symptom severity, experimental evidence examining associations between task-based EFs and mechanically assessed movement reveal stronger relationships. For example, experimentally increasing working memory demands has been found to result in greater motoric activity as assessed by actigraphy in all children regardless of diagnostic status (Rapport et al., 2009). Conversely, a study of task-based inhibition found that while movement increased when transitioning from participating in a control activity with minimal cognitive demands (e.g., drawing in the Paint© program on the computer) to tasks requiring greater cognitive demands, the increases in movement did not appear to be specific to engagement of inhibitory control processes (e.g., Hedges' *g* for conditions with inhibitory demand ranging from 0.11 to 0.27), suggesting that increases in movement likely reflect the engagement of more general task demands or central executive domains of working memory (e.g., attention; Alderson et al., 2012). This effect was replicated subsequently with other cognitive tasks involving non-executive functions (e.g., reaction time; Hudec et al., 2015). Collectively, these findings highlight the need to evaluate the extent to which specific domains of EF (i.e., working memory, behavioral inhibition) may be differentially associated with motoric activity. Further, it is important to note that past work evaluating the relations between task-based EFs and mechanically assessed movement (Rapport et al., 2009; Sarver et al., 2015) may partially reflect the extent to which the data is collected concurrently (i.e., actigraphy data collected during the course of completing a specific EF task). As a result, evaluations of these associations using mechanically-assessed movement during a task that is separate from the tasks assessing the EF constructs of interest are critically needed. In addition to clarifying the relative associations among various methods of measuring EFs and various methods of measuring symptoms, incorporating an objective quantification of movement will also help improve our understanding of the relative contribution of both EF measurement methods in understanding hyperactivity while overcoming a number of limitations previously described.

In sum, two primary methods of quantifying EF (i.e., task-based and questionnaire-based) are both frequently used and demonstrate deficits in youth with ADHD. However, the two EF measurement methods have not been found consistently to be correlated with one another and the literature reveals inconsistent associations between each EF measurement method and symptoms of ADHD such as hyperactivity. These discrepancies reflect measurement limitations that hinder cohesive conclusions from being drawn from the extant literature, and obfuscate knowledge of the true magnitude of the associations between EF and hyperactivity. While most of these limitations have been acknowledged in the literature, no study to date has incorporated novel approaches to measurement (e.g., actigraphy) to overcome some of these limitations and derive better estimates of the associations among EF and symptoms of ADHD. The EF constructs of interest in the present study include working memory and inhibition given past work implicating these areas as key domains of executive functioning (Snyder et al., 2015), a large theoretical literature supporting the importance of inhibition to hyperactivity (e.g., Barkley 1997; Puiu et al., 2018), and experimental evidence that manipulating cognitive demands increases activity level (Rapport, Bolden, Kofler, Raiker, & Alderson, 2009; Alderson et al., 2012). Notably, working memory and inhibition will be evaluated separately given theoretical arguments that inhibition is important to advancing our understanding of hyperactivity (e.g., Barkley 1997) despite recent experimental evidence indicating that inhibition may not be uniquely related to increases in activity level (Alderson et al., 2012) as well as substantial support for a significant association between working memory and activity level (Rapport et al., 2009; Sarver et al., 2015).

The present study has two primary aims. The first aim is to replicate prior work in this area by estimating the strength of association among task-based EF, questionnaire-based EF, and parent-reported hyperactivity/impulsivity. Consistent with past studies, we anticipate that measures of task-based EF and questionnaire-based EF will be weakly related, measures of questionnaire-based EF and parent-reported hyperactivity/impulsivity will be highly related, and measures of task-based EF and parent-reported hyperactivity/impulsivity will be weakly related (e.g., Krieger & Amador-Campos, 2018). Moderate to strong effect sizes with actigraphy in experimental studies (e.g., Rapport et al., 2009) suggest that task-based EFs will be moderately associated with mechanically assessed movement, though we anticipate stronger associations for working memory than inhibition. We also anticipate that parent-reported hyperactivity/impulsivity and mechanically assessed movement will be moderately associated. The second aim of this study is to examine the unique contribution of task-based and questionnaire-based EF to activity level when measured mechanically (i.e., actigraphy). We expect that the removal of a monomethod source of variance (i.e., questionnaire-based EF and questionnaire-based hyperactivity/impulsivity) will result in attenuated associations between questionnaire-based EF and hyperactivity when assessed via actigraphy and relatively larger magnitude associations between task-based EF and hyperactivity.

Method

Participants

Fifty-two children recruited from two sources were combined to allow for examination of all constructs and their associations continuously, consistent with past work demonstrating that symptoms of ADHD such as hyperactivity are continuously and normally distributed in the general population (Marcus & Barry, 2011). Twenty-eight children were directly recruited during their participation in an ongoing summer treatment program (STP) for children with ADHD and related behavioral problems (Pelham & Hoza, 1996). Eligibility for participation in the STP was determined by a Licensed Clinical Psychologist following review of parent and teacher rating scales including the Child Behavior Checklist (Achenbach & Edelbrock, 1983), Disruptive Behavior Disorders rating scale (parent and teacher versions; Pelham et al., 1992), Impairment Rating Scale (parent and teacher versions; Fabiano et al., 2006), as well as a clinical interview with the child's parent. No comorbidities were excluded and children were included if the Licensed Clinical Psychologist determined the child was likely to benefit from treatment in the STP. Additionally, twenty-four children were recruited from the community via flyers, word-of-mouth, email listservs, and advertisement of the study during participation in other ongoing research studies taking place at the university. These children participated in a similar eligibility process in which the identical parent and teacher measures were administered as well as the Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children (K-SADS). This information was reviewed by a Licensed Clinical Psychologist to determine eligibility. All children in this group were typically developing (with no other psychopathology)[2]. All children participating in this study who were prescribed medication for ADHD were asked to withhold medication (with the permission of their prescribing physician) on the day of testing. Additionally, individuals with a Full-Scale IQ (estimated based upon the Weschler Abbreviated Scale of Intelligence) less than 80 were excluded from participation given potential difficulties involved in completing the cognitive tasks.

Because the primary constructs of interest to the present study (e.g., task performance, movement) are inherently continuous and their relationships are best conceptualized as such, the two groups were combined for all analyses consistent with past work in the area (e.g., Eycke & Dewey, 2016; Miranda, Colomer, Mercader, Fernández, & Presentación, 2015). Consequently, the distribution of symptoms was positively skewed due to a larger number of the community children having little to no symptomatology. As a result, bootstrapping and robust standard errors were utilized in all analyses to overcome potential limitations associated with violations of normality and/or heteroskedasticity as recommended (Croux, Dhaene, & Hoorelbeke, 2004; Hayes 2017; Keselman, Wilcox, Othman, & Fradette, 2002; see data analytic plan).

Procedures

All study procedures were approved by the Florida International University Institutional Review Board (IRB) prior to the onset of data collection. A parent of each child in the study completed written informed consent, and each child completed written assent. Parent-reported questionnaire-based EF and ADHD symptom ratings were completed by the child's parent or guardian via an email link sent through REDCap (Research Electronic Data Capture; Harris et al., 2009). Subsequently, children completed a two- to four-hour testing session during which all task-based executive functioning data and objectively measured hyperactivity data were collected as part of a larger battery of neurocognitive tasks in youth with and without disruptive behavior problems. Participating families of children recruited from the community were compensated with a $40.00 gift card and the child received a small toy in exchange for their willingness to participate. Participants recruited from the STP received points to be applied to the program's ongoing point-based behavioral modification system. In order to minimize order and fatigue effects, administration of the cognitive tasks was randomized across participants.

Measures

Questionnaire-based Executive Functioning.—The Behavior Rating Inventory of Executive Functioning (BRIEF) was used as an assessment of questionnaire-based executive functioning over the past 6 months and was completed by parents of children participating at the time of initial intake. Children recruited from the Summer Treatment Program for children with disruptive behavior problems were administered the BRIEF (Gioia, Guy, Isquith, & Kenworthy, 1996), whereas children recruited from the community or through other ongoing studies were administered the BRIEF-2 (Gioia, Isquith, Guy, & Kenworthy, 2015)[3]. The BRIEF consists of 86 items and the BRIEF-2 consists of 63 items. In both versions, item responses range from 0 (never) to 2 (often). Higher scores indicate more difficulty with EFs. The BRIEF has eight scales and the BRIEF-2 has nine scales reflecting various domains of executive functioning. Both versions contain "Working Memory" and "Inhibit" scales, which are the scales of interest to the present study as they provide the closest correspondence to the EF tasks used. Raw scores were used to facilitate comparable interpretation with the Disruptive Behavior Disorders rating scale. To make comparisons across the two versions of the BRIEF as analogous as possible, the eight identical items on the Working Memory subscales from the BRIEF and BRIEF-2 which display excellent reliability (Cronbach's Alpha = 0.95) were retained for analysis (i.e., the two additional Working Memory items from the BRIEF were not used in our analyses). For the Inhibit scale, six items are identical across the BRIEF and BRIEF-2, and these items belong to the Inhibit subscale on both versions. One item ("is fidgety") appears on the BRIEF-2 Inhibit scale and is identical to an item on the BRIEF that was assigned to an "additional clinical items" scale; this item was retained for those participants administered the BRIEF. Finally, one Inhibit subscale item on the BRIEF-2 (“Does not think before doing [is impulsive])” was previously two items on the BRIEF additional clinical items scale (“#79. Does not think before doing” and “#82. Is impulsive”). To maintain comparability across these two versions, we elected to retain the item that provided the greatest reliability. Reliability was compared using all seven of the previously described items combined with either “Does not think before doing” or “Is impulsive.” Reliability was higher when retaining “Is impulsive”, so this item was retained for those who were administered the BRIEF. Overall, reliability on the eight items used in the present study was high (α = 0.96).

Task-based working memory.—To estimate working memory functioning, phonological and visuospatial working memory tasks were administered (PHWM and VSWM, respectively). Both of these tasks have been used extensively in past work examining ADHD-related working memory deficits (e.g., Rapport et al., 2009) and serve as an index of the PHWM and VSWM subsystems described by Baddeley (1996). In the PHWM task, children were presented with a series of 2 to 5 numbers and one capital letter on a computer screen (forming set sizes of 3 to 6 total items) one at a time. Each number and letter (approximately 7 centimeters) appeared on the screen for 800 milliseconds, followed by a 200 millisecond interstimulus interval. The letter never appeared in the first or last position of the sequence to minimize primacy and recency effects, and was counterbalanced across trials to appear an equal number of times in each position. The length of the series varied between 3 and 6 stimuli. Children were required to say the numbers in order (from smallest to largest), followed by the letter. Two research assistants (coder A and B) independently recorded oral responses shielded from the child’s view (interrater reliability = 89.51% agreement). In the event that research assistants were not in agreement, the recording of coder A was used (as coder A was usually a more senior member of the research team). The child’s response was scored as correct for each stimulus (numbers or the letter) recalled in the correct serial placement.

In the VSWM task, children are presented with a configuration of nine, 3.2-centimeter squares in three columns forming an offset 3×3 grid on a computer screen. A series of 2.5 cm black and red dots was presented sequentially in one of the nine squares such that no two dots appeared in the same square during each trial. The length of the series varied between 3 and 6 stimuli presented. Each dot appeared for 800 milliseconds followed by a 200 millisecond interstimulus interval. All dots were black, with the exception of one red dot counterbalanced across trials to appear an equal number of times in each serial position, never appearing first or last. Children were then instructed to recall this sequence on a keyboard (mirroring the 3×3 offset grid) by pressing the keys corresponding to the position of the black dots first, in order, followed by the key corresponding to the position of the red dot last. The last response was followed by an intertrial interval of 1,000 milliseconds as well as an auditory tone to signal the onset of a new trial. The child’s response was scored as correct for each dot recalled in the correct serial position. The average number of stimuli recalled correctly per trial was averaged across all VSWM and PHWM trials and set sizes resulting in a composite metric of overall working memory performance used in the analyses. Higher scores indicate better performance.

Task-based inhibition.—To estimate inhibition, the Stop Signal Task was used. Variants of the Stop Signal Task have been used with children for several years (Schachar, Tannock, & Logan, 1993) to obtain an estimate of a child's ability to successfully inhibit a response. During this task, children were instructed to press corresponding buttons for visual stimuli (namely, left and right trigger buttons on an Xbox© controller) and to withhold their response if the stimulus was followed by the stop stimulus (i.e., an auditory tone). Visual stimuli (Xs and Os) were presented for 1,000 milliseconds and positioned in the center of a computer screen with each stimuli appearing with an equal frequency during four separate experimental blocks lasting 24 trials per block, each block lasting about 30 seconds. Each stimulus was preceded by a fixation point displayed in the center of the screen for 500 milliseconds, indicating that the stimulus would be presented subsequently. An auditory tone (i.e., stop-signal) was presented following presentation of the visual stimuli randomly on 25% of trials. Stop signal delays were initially set at 250 milliseconds and dynamically adjusted by ±50 seconds contingent upon performance on the previous trial (e.g., if the response to the stop signal was not inhibited successfully, the stop signal delay was reduced to 200 milliseconds to make inhibition on the next trial easier to achieve). This algorithm is designed to result in successful inhibition on half of the stop-trials. Children's Stop Signal Reaction Time (SSRT) was calculated following the integration method with go-omissions replaced by maximum reaction times as recommended (Verbruggen et al., 2019) with two modifications. First, the validity check criterion (which states that reaction times should be slower on go trials than on failed inhibition trials) was ignored due to neurophysiological evidence that suggests the go and stop processes may be dependent or interactive (e.g., Colonius & Diederich, 2018; Verbruggen & Logan, 2009). Second, Verbruggen and colleagues recommend that a task block with greater than 15% omission errors (corresponding to 3/24 trials in the present study's task) be eliminated from analyses based on adult samples. However, using this threshold in our sample resulted in substantial data loss. This is consistent with past studies demonstrating that children with ADHD exhibit greater rates of omission errors than controls (e.g., Overtoom, 2002). To address this, past studies have utilized higher omission error thresholds (e.g., Weigard, Heathcote, Matzke, & Huang-Pollock, 2018) than those recommended. As a result, the present study allowed for 33.33% omission errors (8/24 trials). Notably, task performance data on children with <15% and <33% omission errors did not differ significantly from one another and were highly correlated ($r = 0.95$). The child's SSRT was averaged across all four blocks to form a single score reflecting inhibitory control. Scores were then reverse coded so that higher scores indicate better performance.

Parent-reported hyperactivity.—The Disruptive Behavior Disorders rating scale (DBD; Pelham et al., 1992) was used as a measure of parent-reported hyperactivity/impulsivity. The DBD is a 45-item rating scale corresponding to DSM symptom dimensions of ADHD, oppositional defiant disorder, and conduct disorder. Parents rated each one of these items on a scale ranging from not at all (0) to very much (3) with respect to the frequency of occurrence of the corresponding item. Higher scores indicate greater symptomatology. The present study utilized the sum of the raw score of the nine items comprising the hyperactivity/impulsivity (i.e., H/I) subscale. Total scores on the nine ADHD-H/I items ranged from 0 to 27, which represent the minimum and maximum potential scores. In the present sample, the nine ADHD-H/I items demonstrated excellent reliability (Cronbach's Alpha = 0.95). As aforementioned, the distribution of scores in our two recruitment samples overlapped substantially.

Mechanically-assessed movement.—Actigraphs were used to estimate activity level objectively (i.e., hyperactivity). Specifically, children wore a small, watch-like device (MicroMini Motionlogger; Ambulatory Monitoring Inc., 2004) placed on their non-dominant hand and opposite ankle while participating in the study. Actigraphs contain an acceleration-sensitive sensor that records motor movement 16 times per second. Actigraphy has an estimated reliability of 0.90 to 0.99 when placed on the same location on the same individual (Tryon, 1985). These estimates were collapsed into 1-minute epochs and scaled (divided by 100) for the purpose of this study. The device was set to Proportional Integrating Measure (PIM) mode, which measures the intensity of movement (i.e., determines gross activity level). Data were downloaded and analyzed using the Action W-2 software program (Ambulatory Monitoring Inc., 2004) to calculate mean activity rates for each child during each condition of interest (described below). Higher scores indicated greater movement. In order to prevent artificial inflation of the relation between EF and actigraphy, we opted to use actigraphy data collected from alternate tasks than tasks used as predictors in tier II (described below). Specifically, we measured movement during the Sustained Attention to Response Task (SART). Notably, actigraph was analyzed during a task with some cognitive demand (rather than a control condition) as previous work (e.g., Alderson et al., 2012; Hudec et al., 2015) has shown greater variability in movement during cognitively demanding, but not control, conditions. As a result, we aimed to evaluate mechanically-assessed movement during a condition under which range restriction would be prevented that would allow for meaningful relationships with actigraphy to be detected.

Data analytic plan

Tier I: Correlations.—Correlations across all EF (both questionnaire-based and task-based) and hyperactivity (both parent-reported and mechanically-assessed) measures were evaluated to estimate the relationships among various measurement methods.

Tier II: EF measurement methods predicting mechanically assessed movement.—To estimate the unique contribution of different methods of assessing EF (e.g., task-based, questionnaire-based) to the prediction of mechanically-assessed movement, two regression models were conducted. These examined the extent to which task-based EF and questionnaire-based EF differentially predict mechanically assessed movement. Model one compared task-based working memory and questionnaire-based working memory, and model two contrasted task-based inhibition and questionnaire-based inhibition. This was done to directly compare two methods of examining, ostensibly, the same EF construct.

All analyses were conducted using R 3.5.2. The lavaan package (Rosseel 2012) was used with bias-corrected bootstrapped 95% confidence intervals (CIs) based on 5000 bootstrapped samples. To resolve for missing data (range = 0% to 40.38% depending on task and/or measure, mean = 9.5%), Full Maximum Likelihood Estimation (FMIL) was conducted in R with robust standard errors (which accounts for deviations in normality) as recommended (Allison, 2012; Little et al., 2014). Auxiliary predictor variables were included such that any EF measure (task-based or questionnaire-based EF) or symptom measure (mechanically-assessed movement or parent-reported hyperactivity/impulsivity) that was not present in a given model was included as a predictor of missing data (Graham, 2003).

Results

Tier 1: Correlational analyses

Questionnaire-based working memory and questionnaire-based inhibition were highly correlated with one another ($r = 0.76$, $p < 0.001$) and both were highly correlated with parent-reported hyperactivity/impulsivity (rs = 0.80 – 0.90, ps < 0.001). Task-based working memory and task-based inhibition were moderately correlated with one another ($r = 0.50$, $p < 0.001$). Task-based working memory was highly associated with parent reported hyperactivity/impulsivity ($r = -0.74$, $p < 0.001$), while task-based inhibition was moderately related to parent-reported hyperactivity/impulsivity ($r = -0.34$, $p < 0.05$). Task-based working memory and questionnaire-based working memory were moderately associated ($r = -0.60$, $p < 0.001$) whereas task-based inhibition and questionnaire-based inhibition were more weakly (and not significantly) associated with one another ($r = -0.32$, $p = 0.06$). Mechanically-assessed movement was moderately correlated with parent-reported hyperactivity/impulsivity ($r = 0.39$, $p < 0.05$), questionnaire-based inhibition ($r = 0.41$, $p < 0.05$), task-based inhibition ($r = -0.44$, $p < 0.05$), and task-based working memory ($r = -0.45$, $p < 0.05$), but weakly (and not significantly) related to questionnaire-based working memory ($r = 0.20$, $p = 0.34$). See table 2.

Tier 2: Regression analyses

Model 1: Questionnaire-based and task-based working memory.—Model 1 aimed to estimate the relative contribution of task- and questionnaire-based working memory in predicting mechanically assessed movement. Task-based and questionnaire-based working memory significantly covaried (B = −0.59, $p < 0.001$, SE = 0.09, 95% CI = −0.77 to −0.41). Task-based working memory did not significantly predict mechanically-assessed movement (B = −0.46, $p = 0.05$, SE = 0.21, 95% CI = −0.86 to −0.05) after controlling for questionnaire-based working memory scores. Similarly, questionnaire-based working memory did not significantly predict mechanically-assessed movement (B = −0.06, $p = 0.77$, SE = 0.21, 95% CI = −0.47 to 0.35) after controlling for task-based working memory performance. See figure 1.

Model 2: Questionnaire-based and task-based inhibition.—Model 2 aimed to estimate the relative contribution of task- and questionnaire-based inhibition in predicting mechanically assessed movement. Task-based and questionnaire-based inhibition significantly covaried (B = −0.30, $p < 0.05$, SE = 0.13, 95% CI = −0.54 to −0.05). Task-based inhibition significantly predicted mechanically-assessed movement (B = −0.33, $p < 0.05$, SE = 0.14, 95% CI = −0.60 to −0.06), such that those with slower, or worse, SSRTs exhibited significantly greater movement after controlling for questionnaire-based inhibition.

In contrast, questionnaire-based inhibition did not significantly predict mechanically-assessed movement independently (B = 0.23, $p = 0.17$, SE = 0.15, 95% CI = −0.05 to 0.52). See figure 1.

Discussion

The literature to date suggests that the two primary methods of assessing executive functioning (EF) in ADHD are unrelated to one another, and that each method demonstrates a different pattern of associations with symptoms of ADHD. These discrepant findings raise significant questions regarding the extent to which tasks assessing EFs or other approaches to assessing symptoms of ADHD (e.g., actigraphy) assist in improving our understanding of the role of EF in ADHD symptomology. The present study sought to clarify these relations by incorporating a multi-method approach to assessment of both EF and symptoms of hyperactivity/impulsivity using well-developed cognitive tasks and an objective assessment of activity level. This approach was necessary to address the limitations of extant work in this area and to clarify the extent to which EF tasks may be helpful in advancing our understanding of ADHD symptomatology.

Consistent with past work, performance across the two measures of task-based EF (i.e., working memory, inhibition) were moderately correlated with one another and the questionnaires presumed to assess these constructs were strongly correlated with one another. Similarly, and unsurprisingly, questionnaire-based EFs and parent-reported hyperactivity/impulsivity were strongly correlated (*r*s ranging from 0.80 to 0.90; both $p < 0.001$; Krieger & Amador-Campos, 2018; Toplak et al., 2008). Task-based inhibition was weakly to moderately associated (*r*s ranging from −0.31 to −0.34) with parent-reported hyperactivity/impulsivity and both questionnaire-based EF measures, a magnitude similar to some findings (e.g., Hummer et al., 2011; Mahone et al., 2002) and larger than others (e.g., Shuster & Toplak, 2009; McAuley et al., 2010). Collectively, this pattern of findings is consistent with past work in this area indicating that mono-informant and mono-method biases may largely drive these respective associations (e.g., Eycke & Dewey, 2016; Silver 2014) such that matched methods were found to be highly correlated while mixed methods were found to be only weakly to moderately associated.

Contrary to expectations (Toplak 2013), task-based working memory was strongly correlated with parent-reported hyperactivity/impulsivity ($r = -0.74$, $p < 0.001$) and moderately to strongly correlated with both measures of questionnaire-based EF (*r*s = −0.60 to −0.71; *p*s < 0.001). This finding highlights how well-designed measures of EF may assist in clarifying the relation among ADHD symptoms and executive functioning. That is, many of the studies cited by Toplak and colleagues (2013) used traditional neuropsychological working memory measures such as Digit Span or N-back tasks. Our findings are consistent with considerable work demonstrating that these traditional clinical measures may lack the sensitivity to detect subtle impairments in working memory in disorders such as ADHD (e.g., Snyder et al., 2015; Wells, Kofler, Soto, Schaefer, & Sarver, 2018). Namely, these assessments typically estimate multiple aspects of EF rather than assessing specific cognitive domains of impairment (e.g., working memory) and are better suited for assessing more broad and severe EF impairments (Snyder et al., 2015). Further, “all-or-nothing” scoring approaches are often used on digit span tasks despite evidence that this approach reduces reliability compared to the partial scoring approach used on the current tasks (Wells et al., 2018). In contrast, the well-designed working memory task used in the current study was strongly associated with a questionnaire-based assessment of working memory functioning as well as parent reports of hyperactivity/impulsivity in our sample.

The pattern of relations - whereby questionnaire-based EFs are highly related to parent-reported symptoms, and task-based EFs lesser so (besides the exception found in the present study concerning task-based working memory) - is predominantly what contributes to the discrepancies in the literature to date. This pattern disallows the predictive utility of EF assessments to be unbiasedly compared due to the measurement methods shared between one of the EF methods (questionnaire-based EF) and parent-reported symptoms. In an effort to test the idea that mono-method biases drive the pattern of associations found, this study incorporated actigraphy and results revealed associations that were consistent with expectations. Specifically, parent-reported hyperactivity/impulsivity and mechanically-assessed movement were moderately correlated consistent with past work (e.g., Rapport et al., 2009). Further, mechanically assessed movement was moderately associated with all EF assessments (i.e., questionnaire-based, task-based) with one exception (questionnaire-based working memory). Notably, the magnitude of the association of mechanically assessed movement with various measures of EF was similar (correlations with task-based working memory, task-based inhibition, and questionnaire-based inhibition ranged from 0.41 to 0.45). These findings highlight that when the effects of mono-method bias are reduced, questionnaire-based and task-based EF demonstrate similar magnitude correlations with symptoms of ADHD when measured objectively. This indicates that more objective approaches to behavioral assessment such as actigraphy may be a useful tool with which to compare the utility of EF measurement methods.

Critically, the results of the tier 2 analyses illustrate that with methodological biases reduced and with the incorporation of additional measurement approaches (e.g., more sensitive EF measures, actigraphy), task-based EF assessments show promise in advancing our understanding of ADHD symptomatology. Specifically, both task-based EF measures had relatively larger magnitude effects (standardized betas ranged from −0.46 to −0.33) with respect to predicting mechanically assessed movement relative to their questionnaire-based counterparts (standardized betas ranged from −.06 to 0.23; see figure 1). Further, while task-based inhibition was a statistically significant predictor and task-based working memory was not - perhaps due to the unexpectedly large covariance between predictors in the working memory model - the relative magnitude of the regression coefficients for task-based EFs in tier 2 (task-based working memory slightly larger than task-based inhibition) are consistent with past experimental studies (Rapport et al., 2009; Sarver et al., 2015) demonstrating that increasing working memory demands, but not inhibitory demands (Alderson et al., 2012; Hudec et al., 2015), are associated with increased movement.

In addition to the role of measurement method, it is important to consider the demands of the setting in which these data are collected and their correspondence to an informant's perspective. For example, mechanically-assessed movement was collected in the context of a moderately cognitively demanding task, whereas parent reports of hyperactivity/impulsivity may reflect behavior across various contexts. Concurrent collection of parent hyperactivity/impulsivity ratings while completing these tasks, or mechanically assessed movement assessed during recreational activities, may show better correspondence. Relatedly, mechanically-assessed movement collected during cognitively demanding situations (e.g., testing sessions such as in the present study, or concurrent collection of actigraphy data in the classroom) may correspond better to teachers' insights. Collectively, our results indicate that actigraphy may be a useful tool for understanding these patterns. For example, this study along with previous work (e.g., Alderson et al., 2012) demonstrate that children display more variability in movement during cognitively demanding conditions. A related benefit of task-based EF is that when EF demands are experimentally elicited, specific symptoms or domains of impairment may be exacerbated; this allows for a more exact understanding of EF's role in psychopathology (e.g., Kofler et al., 2016; Rapport et al., 2009). Additionally, rating scales may benefit from added specificity that reflects the child's behavior in specific contexts rather than broadband impressions. This is likely to be true particularly in contexts where these symptoms may not be present or as impairing (e.g., during recreational activities).

The current study has several notable methodological strengths, such as the incorporation of multiple methods of assessment, the use of objective quantification of activity level, and the use of a sample of mechanically-assessed movement collected during a task that was different than tasks used as predictors to limit methodological similarity. Despite these strengths, interpretation of the present study results should be tempered in light of some limitations. For example, both the BRIEF and BRIEF-2 were used. Fortunately, reliability on the Working Memory and Inhibit scales derived from items across both versions for use in the present study was very high (α = 0.95–0.96). Relatedly, the present study's two indices of hyperactivity did not have perfect correspondence; parent-report was of both hyperactivity and impulsivity, whereas mechanically-assessed movement is only a proxy of hyperactivity, but not necessarily impulsivity. However, upon further examination, the four hyperactive/impulsive items that relate explicitly to motoric movement were similarly correlated with actigraphy ($r = 0.41$, $p < 0.05$). Further, future studies should incorporate larger and more diverse samples. A larger sample may allow for more quantitatively complex analyses, such as looking at movement during multiple conditions or integrating multiple informant reports of hyperactivity. Additionally, though we attempted to limit shared method variance by collecting actigraphy on a task separate from tasks of interest, the timescale was still shared insofar as both actigraphy and task-based EF occurred in a laboratory-based setting. Relatedly, future studies would benefit from consideration of the role of teacher and parent reports and their correspondence or lack thereof to the contextual demands during which mechanically-assessed movement data is gathered. Finally, while the present study only examined hyperactivity, consideration of other EFs (e.g., vigilance, set-shifting) and symptoms of ADHD (e.g., inattention) would provide increased clarity regarding the various approaches to measuring EF and symptomology in the disorder.

Collectively, the results of the current study replicate past work demonstrating that questionnaire-based working memory and inhibition, such as the Working Memory and Inhibit subscales of the BRIEF, are largely redundant with measures of parent-reported symptoms (e.g., Barkley & Fischer, 2011; Bünger et al., 2019; Davidson et al., 2016;

McAuley et al., 2010; Silver 2014; Eycke & Dewey, 2016; Vogt & Shameli, 2011). This study is the first to incorporate objectively-measured symptoms (i.e., actigraphy) and experimental tasks assessing specific domains of EF (i.e., working memory, behavioral inhibition) to attempt to reduce the measurement concerns noted in prior work and provide quantitative evidence that when these limitations are addressed, questionnaire-based EF and task-based EF assessments demonstrate similar magnitude correlations with objectively-measured symptoms of ADHD. Notably, when predicting this outcome with reduced measurement biases, both task-based EFs accounted for a greater amount of variance relative to questionnaire-based EFs. Alternative approaches to measuring symptoms (e.g., actigraphy) - particularly within contexts in which they may intensify (e.g., when experiencing cognitive demand) - are likely to further elucidate the relation between EF and symptoms of ADHD, not only due to a reduction in measurement similarity, but also due to the concurrent elicitation and measurement of symptoms in specific contexts. In sum, the pattern of findings throughout the literature to date likely reflect substantial measurement concerns such as mono-method biases, mono-informant biases, and choice of task-based EF measure. Thoughtful task and questionnaire design, as well as innovative methods of measuring symptoms, should be explored in future studies of executive functioning.

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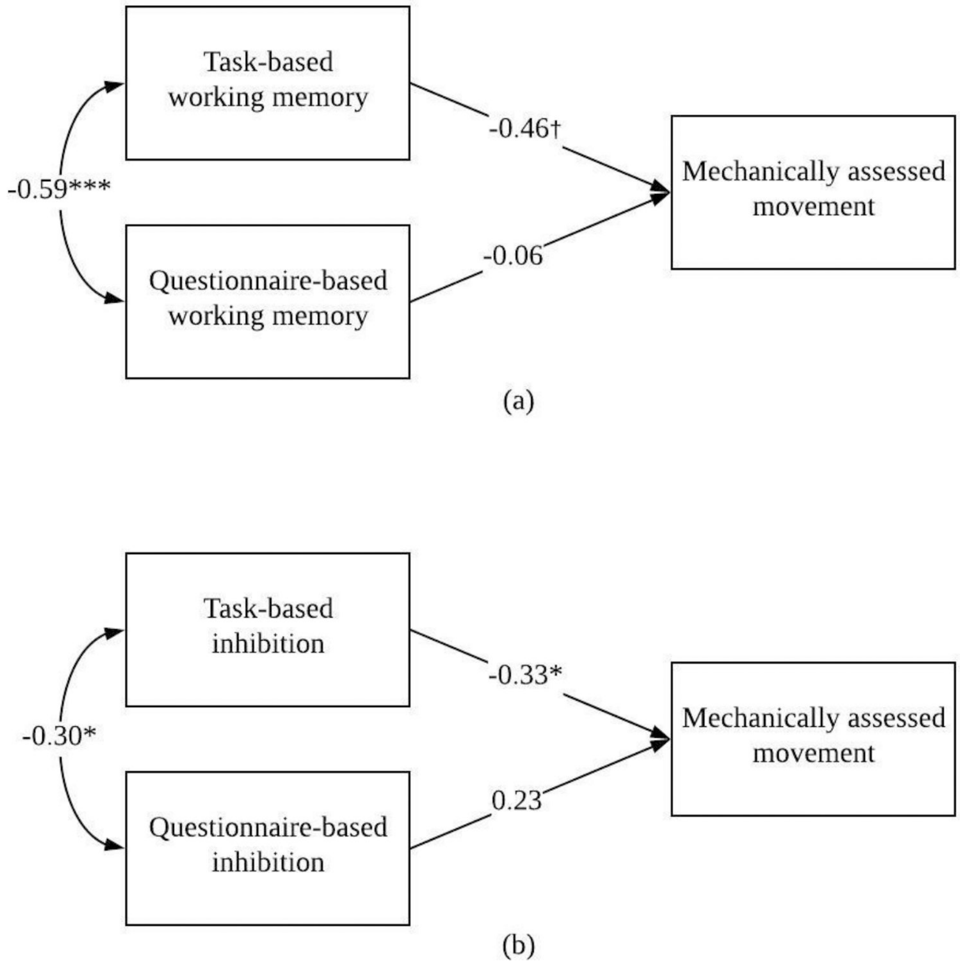

Fig. 1.

Path diagrams illustrating standardized betas for tier 2 analyses. Panel (a) illustrates model one; panel (b) illustrates model two. †$p < .10$; *$p < .05$; **$p < .01$; ***$p < .001$

Table 1

Demographic information and descriptive statistics

	Total (*n* = 52)	**STP (*n* = 28)**	**Community (*n* = 24)**
	Percentage (*n*)	**Percentage (*n*)**	**Percentage (*n*)**
Sex			
Male	67.3 (35)	89.3 (25)	41.7 (10)
Female	32.7 (17)	10.7 (3)	58.3 (14)
Race			
White	88.5 (46)	85.7 (24)	91.7 (22)
Black	5.8 (3)	10.7 (3)	0 (0)
Asian	19 (1)	3.6 (1)	0 (0)
>1 race	3.8 (2)	0 (0)	8.3 (2)
Ethnicity			
Hispanic	92.3 (48)	85.7 (24)	100 (24)
Non-Hispanic	7.7 (4)	14.3 (4)	0 (0)
	M (SD)	**M (SD)**	**M (SD)**
Age	9.87 (1.41)	9.46 (1.55)	10.37 (1.06)
DBD ADHD	21.47 (18.29)	35.38 (10.79)	5.74 (10.50)
DBD H/I	9.59 (8.77)	16.23 (6.45)	2.08 (3.12)
Actigraphy PIM	20.04 (16.91)	25.54 (18.80)	12.44 (10.32)

STP = Participants recruited from the summer treatment program. Community = Participants recruited from community sources. ADHD = attention-deficit/hyperactivity disorder. DBD ADHD = sum of the 18 items comprising the ADHD subscales of the Disruptive Behavior Disorder rating scale. DBD H/I = sum of the 9 items comprising the ADHD Hyperactivity/Impulsivity subscale. PIM = Proportional Integrating Measure Mode. Groups significantly differed in their levels of movement; $t(27.39) = -2.49$, $p < .05$.

Table 2

Pearson correlation coefficients among executive functioning and symptom measures

Variable	1.	2.	3.	4.	5.	6.
1. Task-based WM	-					
2. Task-based inhibition	0.50***	-				
3. Questionnaire-based WM	−0.60***	−0.31†	-			
4. Questionnaire-based inhibition	−0.71	−0.32†	0.76***	-		
5. Parent-reported H/I	−0.74***	−0.34*	0.80***	0.90***	-	
6. Mechanically assessed movement	−0.45*	−0.44*	0.20	0.41*	0.39*	-

† $p < .10$;

* $p < .05$;

** $p < .01$;

*** $p < .001$.

WM = working memory. H/I = hyperactivity/impulsivity.