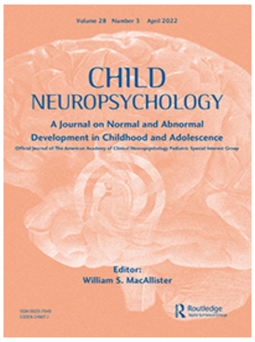

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Child Neuropsychology

A Journal on Normal and Abnormal Development in Childhood and Adolescence

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ncny20

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To cite this article: Daniel T. Burley, Kate L. Anning & Stephanie H. M. van Goozen (2022) The association between hyperactive behaviour and cognitive inhibition impairments in young children, Child Neuropsychology, 28:3, 302-317, DOI: 10.1080/09297049.2021.1976128

To link to this article: https://doi.org/10.1080/09297049.2021.1976128

CHILD NEUROPSYCHOLOGY
2022, VOL. 28, NO. 3, 302–317
https://doi.org/10.1080/09297049.2021.1976128

The association between hyperactive behaviour and cognitive inhibition impairments in young children

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ABSTRACT

Hyperactivity is one of the core features of attention-deficit hyperactivity disorder (ADHD), and yet there is evidence that hyperactive behavior in children with ADHD is not ubiquitous and could be a compensatory response to high cognitive demands. No research has yet objectively measured hyperactive behavior in young children who are demonstrating early signs of ADHD or examined the role of emotional state on hyperactivity levels.The current study measured motor activity using actigraphy during baseline, cognitive inhibition (Flanker task), and emotion arousing (Impossibly Perfect Circles task) conditions in 95 children aged 4–7 years old with developmental difficulties, including emerging symptoms of ADHD. We examined the relationship between objectively recorded activity, parent-rated hyperactivity problems, using the Strengths and Difficulties Questionnaire (SDQ), and cognitive inhibition task performance. Parent ratings of hyperactivity (but not inattention) symptoms were positively related to recorded hyperactivity, and this relationship was specific to activity measured during the cognitive inhibition task. Impaired cognitive inhibition performance was related to increased measured movement and this association was strongest in children who were rated as having the highest levels of hyperactive behavior. These findings confirm theoretically predicted associations between objectively recorded hyperactivity and impaired executive functioning and support the notion that hyperactivity in children emerges in response to high cognitive demands. The results encourage further investigation into the role of hyperactivity as a transdiagnostic dimension that can explain variation within and between different types of diagnostic classifications.

ARTICLE HISTORY
Received 10 December 2020
Accepted 31 August 2021

KEYWORDS
Hyperactivity; attention deficit hyperactivity disorder (ADHD); actigraphy; cognitive inhibition

Attention Deficit Hyperactivity Disorder (ADHD) is one of the most prevalent childhood psychiatric disorders – estimated prevalence within children is 7.2% (Thomas et al., 2015) – and is associated with a range of long-term negative outcomes including lower academic achievement, reduced income, unemployment, substance abuse, dysfunctional interpersonal relationships, antisociality and risk health behaviors (Erskine et al., 2016). ADHD represents a complex and heterogenous neurodevelopmental disorder characterized by a persistent pattern of inattention and/or hyperactivity/impulsivity (American Psychiatric Association, 2013). Hyperactivity or excessive motor activity is considered

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Supplemental data for this article can be accessed at https://doi.org/10.1080/09297049.2021.1976128.

one of the core features of the disorder and represents the majority of symptoms identified within the impulsivity/hyperactivity component of DSM-5 ADHD diagnosis (APA, 2013).

Subjective measures have been traditionally the most common metric of hyperactivity (e.g., symptoms scores, clinical ratings), with objective measures of hyperactivity also utilized including actigraphs, infrared motion and pedometers. There has been a disconnect between behavioral ratings and direct objective measurement of hyperactivity with only moderate overlap (r = .32 – .58; Rapport et al., 2006). Subjective measures have also defined distinct ADHD subtypes based on the severity of hyperactivity symptoms, but this distinction has not been reflected in objective measurement of hyperactivity where elevated motor activity is observed regardless of ADHD subtype (Kofler et al., 2016). This has led to the proposal that informant ratings of hyperactivity reflect more than raw motor activity levels (Kofler et al., 2016). In addition, objective measures of hyperactivity have found increased locomotor activity across children/adolescents and adults with ADHD (see Murillo et al., 2015, for a meta-analysis of the literature) and increased locomotor activity has also been found to be a longitudinally sensitive marker of ADHD-recovery (Cheung et al., 2016). This suggests that excessive motor activity is an important marker of ADHD, yet whether hyperactivity can be considered as a homogenous and universal feature of ADHD has been questioned by evidence that the presence and severity of hyperactivity has varied dependent on the task or activity the individual was engaged in when their activity levels were indexed (Kofler et al., 2016). Understanding environmental factors that influence hyperactivity is important for theoretical conceptualizations of ADHD in order to specify whether hyperactivity is a ubiquitous symptom or a secondary consequence of alternative impairments. This issue has further implication for understanding whether hyperactivity represents a transdiagnostic symptom that extends beyond ADHD and across wider neurodevelopmental difficulties.

Prominent theoretical models of hyperactivity within ADHD have implicated associated impairments in executive functions. Inhibition models of ADHD have hypothesized that excessive motor activity is a byproduct of core inhibitory deficits including the ability to stop pre-potent/ongoing responses, interference control (the capacity to exclude non goal-directed information), and delay gratification (Barkley, 1997; Sonuga-Barke, 2002). There is evidence to suggest an underlying association between deficient inhibition and ADHD including hyperactivity; children with ADHD demonstrate impairments in executive functions including response inhibition (Berlin & Bohlin, 2002; Berlin et al., 2004), altered functional neural activity during inhibition tasks (Booth et al., 2005), and hyperactive children with traumatic brain injuries show similar inhibitory response deficits to children with ADHD (Konrad et al., 2000). Objectively measured hyperactivity has also been associated with lower inhibition performance across a sample of children diagnosed with ADHD and typically developing children (mean age was 11 years old) (Murillo et al., 2015). Alternative studies that have objectively measured hyperactivity have questioned whether inhibitory deficits underlie excessive activity levels within children and instead suggested that increased motor activity may serve a functional role, reflecting an attempt to increase cortical arousal in order to meet basic attentional or working memory task demands (Alderson et al., 2012; Dekkers et al., 2021; Kofler et al., 2016; Patros et al., 2017). Although the specific executive function/s that underpin hyperactivity remains an area for further investigation, there is evidence to suggest that the presence and magnitude of hyperactive behavior in ADHD is influenced by environmental task conditions and is most evident under conditions that place high demand on executive functioning (Kofler et al., 2016). Interestingly, to our knowledge, no study has examined whether objectively measured hyperactivity is also influenced by the individual's affective state, despite the ADHD phenotype being characterized by diminished frustration tolerance, increased emotional impulsivity and deficient emotional self-regulation that are linked with greater severity of symptoms (Faraone et al., 2019; Seymour et al., 2019). There is also an increased recognition of the importance to consider both cognitive and emotional influences in relation to ADHD within developmental research designs (Musser & Raiker, 2019).

Prior research has typically examined objectively measured hyperactivity in relation to ADHD using a categorical approach; that is, by comparing small groups of children (often boys) diagnosed with ADHD to typically developing children. ADHDis identified more often by teachers than parents or physicians meaning that the process for diagnosis is not often initiated until the child enters formal schooling (Sax & Kautz, 2003), which is likely an important contributing factor that the mean age for childhood diagnosis is not until seven years old (Visser et al., 2014). Studies have therefore typically investigated hyperactivity within children aged seven years and older, despite ADHD behavioral and cognitive symptomatology being present at a younger age (Arnett et al., 2013). In addition, examining ADHD as a categorical disorder ignores the continuous distribution of ADHD symptoms (i.e., hyperactivity) within the general population, as well as the comorbidity of symptoms across neurodevelopmental disorders (Fair et al., 2012; Musser & Raiker, 2019). Brocki et al. (2010) explored whether the two main dimensions of ADHD – inattention and hyperactivity/impulsivity – were independently associated with measured activity levels within a large population-based sample of 401 children aged 6–12 years old that included no children diagnosed with ADHD. They found that dimensional ratings of hyperactivity symptoms (but not inattention) were modestly associated with increased measured activity levels during a cognitively demanding executive function task. They observed no effect of child age on this relationship. This suggests that the dimensional relationship between rated and observed hyperactivity mirrors findings from studies examining children at the extreme end of a hyperactivity dimension (i.e., children with diagnosed ADHD). However, Brocki et al. (2010) did not examine patterns of measured hyperactivity during differing environmental conditions, nor did they directly investigate the relationship between measured hyperactivity and cognitive task performance meaning that no clear interpretations could be offered regarding the processes underlying hyperactivity. In addition, the dimension of ADHD symptomatology was likely truncated within this study as the sample included children up until the age of 12 years old yet children with a diagnosis of ADHD were removed from the sample. It is therefore important to investigate patterns of observed hyperactivity across varying task conditions within young children with emerging hyperactivity but who are prior to a diagnosis of ADHD.

Current study

The present study extended previous research to investigate objectively measured activity levels during baseline, cognitive inhibition, and emotional task conditions within young children aged 4–7 years old identified as at-risk for mental health problems; this included children demonstrating early ADHD symptoms. We also measured behavioral ratings of ADHD, including the separate dimensions of inattention and hyperactivity/impulsivity, and cognitive inhibition task performance. The study aimed to investigate: 1) The relationship between behavioral ratings of ADHD and objectively recorded activity under varying environmental task conditions, and 2) whether cognitive inhibition deficits are associated with increased levels of measured activity within children, and whether this relationship is stronger in those with higher levels of ADHD symptoms. Firstly, we hypothesized that ratings of ADHD symptoms – specifically higher ratings of hyperactivity consistent with previous research (Brocki et al., 2010) -would be associated with increased activity levels, and this relationship between rated and objective hyperactivity would be specific to the cognitive inhibition task which places a greater demand on executive functioning. That is, we expected no relationship between parent rated and objectively recorded hyperactivity during the baseline and emotional task conditions where executive functioning demands are low. Secondly, we predicted that low cognitive inhibition task performance would be associated with increased measured activity levels based on theoretical models of impaired executive functioning underlying hyperactivity (Barkley, 1997; Sonuga-Barke, 2002). We were further interested to explore the importance of underlying executive function impairments to hyperactivity within young children who were most at risk of ADHD difficulties, and therefore also made a tentative subsidiary prediction that symptom severity as measured by higher behavioral ratings of hyperactivity would moderate, specifically increase, the expected relationship between impairments in cognitive inhibition and measured hyperactivity.

Materials and methods

Participants

One-hundred and fifteen children were referred to the Neurodevelopment Assessment Unit (NDAU; https://www.cardiff.ac.uk/neurodevelopment-assessment-unit) at Cardiff University by their teachers for a range of socio-emotional, cognitive and behavioral difficulties. The final sample consisted of 95 children (38 female) aged 5–7 years old (M = 74.64 months, SD = 11.88, range = 52–95 months). Actigraph data could not be obtained across both the baseline and Flanker task for 19 children (6 children asked for the Actigraph to be removed prematurely and the remaining 13 children did not pass the practice phase of the Flanker task) and one child's activity data were omitted for extreme values. Written informed consent was obtained from the parent or caregiver for each child. Children and their parent/caregiver attended two assessment sessions where the child completed a range of tasks and were invited to take part in the current procedure involving the Actigraph.All experimental procedures were approved by Cardiff University (EC.16.10.11.4592GR).

Actigraph

Child motor activity was measured using a compact, light-weight and portable actigraph device (Actiwave Cardio System, CamNTech) that was worn on the child's sternum. There is evidence that Actigraphs may have improved sensitivity for detecting hyperactivity compared to alterative objective measures such as infrared motion technologies during high cognitive/low stimulation settings (Kofler et al., 2016). The actigraph consisted of two electrodes connected by a short lead that clip onto two standard electrocardiogram pads attached to the skin. The actigraph contained a tri-axial accelerometer that detected the degree of movement by the wearer at a 32 Hz sampling rate. Activity was defined as the amount of movement within one-second epochs based on the position of the accelerometer along the Y axis (with '0′ reflecting no movement and higher numbers reflecting increased movement). The Y-axis was parallel to "head-to-toe. "The child wore the actigraph for approximately 20 minutes in total across an initial baseline phase, a cognitive task and an emotional task that are described below.

Behavioral ratings of ADHD symptoms

Rated ADHD symptoms were established using the parent-informant version of the Strengths and Difficulties Questionnaire (SDQ; Goodman,1997). The SDQ is a 25-item screening measure to assess the child's functioning across emotional, conduct, inattention/hyperactivity, and peer relationships problems, as well as examining prosocial behaviors. The inattention/hyperactivity subscale consists of 5-items each scored from 0 ("Not true"), 1 ("Somewhat true") and 2 ("Certainly true") tapping into inattention (e.g., "Easily distracted, concentration wanders," "sees tasks through to the end") and hyperactivity/impulsivity (e.g., "Restless, overactive, cannot stay still for long," "Constantly fidgeting or squirming" and "Thinks things out before acting"). Total inattention/hyperactivity symptoms range on the SDQ from 0–10. As can be seen in Table 1, the sample showed a high level of inattention/hyperactivity symptoms with 56.8% of the sample showing 'high'or "very high" scores on the SDQ inattention/hyperactivity subscale. Parent ratings on the SDQ inattention/hyperactivity subscale have been linked with ADHD diagnosis in children (Becker et al., 2004). We also calculated individual dimensional score for the inattention items (from 0–4) and hyperactivity items (0–6) through the sum of the individual items, as well as the overall subscale score. Missing SDQ item-scores were calculated based on the mean scores for the remaining items and rounded to the nearest whole number. Each SDQ subscale

Table 1. Descriptive data for actigraphy movement, strengths & difficulties questionnaire (SDQ) scores and Flanker task performance.

	Mean (SD)	Range
Actigraphy movement		
Baseline	2.10 (2.72)	0–13.08
Flanker task	2.90 (3.79)	0.01–19.72
Impossibly Perfect Circles task	1.77 (2.12)	0–14.76
SDQ		
Inattention/hyperactivity	7.45 (2.60)	0–10
Hyperactivity	4.27 (1.80)	0–6
Inattention	3.17 (1.12)	0–4
Flanker task		
Raw score	30.19 (11.58)	8–40
Computed score	4.22 (1.84)	1–7.95

demonstrated acceptable internal consistency, although we note the lower reliability estimate for peer problems (Cronbach's α: Emotional problems = .76, Conduct problems = .77, Hyperactivity = .77, Peer problems = .58, Prosocial = .77).

Task conditions

Actigraph data were collected during a baseline condition, a cognitive Flanker task, and during an emotional task. Cognitive task performance was also examined during the Flanker task. Each child completed this procedure in the same order, although nine children asked for the Actigraph to be removed after the Flanker task meaning that the final participant sample for the emotional task was lower (n = 86).

Baseline

Movement data was assessed during a two-minute baseline condition where children were asked to sit still in a chair at a desk.

Flanker task

Children completed the Flanker task from the NIH Toolbox Cognition Battery (Zelazo et al., 2013), which is a measure of inhibitory control in the context of selective visual attention. The task was administered on an electronic tablet with children seated in front of the device and they provided their responses via the touch screen monitor. The format and scoring of the task are automatically provided by the software. The task consisted of a practice block, the "fish block" and the "arrows block." The task required the child to focus on a fish in the middle of the screen while inhibiting attention to additional fish flanking it and press one of two buttons to indicate which direction the middle fish was pointing. The word "middle" appeared visually on the screen prior to each trial along with an auditory stimulus stating "middle" to remind participants to attend to the middle fish. The fish flanking the middle fish were pointing either in the same direction (congruent) or in the opposing direction (incongruent). Children received four practice trials (two congruent and two incongruent) and needed to provide the correct answer for three trials to advance to the main test block. During this practice block, the children received auditory feedback after their response either stating "Good job" or highlighting the correct choice. If the children did not meet criterion during the practice block, they were provided with three further blocks of four practice trials and if they still did not meet criterion the task was terminated. As mentioned earlier, 13 children did not pass the practice block of the Flanker task and therefore their data was omitted. Within the "fish block," children were presented with 20 trials and their accuracy was scored across these trials. If the child made errors in response to more than one congruent and one incongruent trial, then the task was terminated after the "fish block," but if they made less errors than this threshold then the child progressed to the "arrow block." The task remained the same in the "arrow block" and 20 further trials were administered, but this version used arrows instead of fish. The number of accurate responses were determined for each child and reflect in their raw score from 0–40.

A further computed score was generated by the software ranging from 0–10 that reflected children's accuracy and, where appropriate, also their reaction time performance during the flanker task. For this computed score, each accurate response received a value of

0.125 and therefore accuracy scores ranged from 0–5, with a maximum score of 5 accuracy points reflecting perfect responses across both the "fish block" and "arrows block." For children that obtained an accuracy of 80% across both the "fish block" and the "arrow block," their computed score also included a reaction time score added to their accuracy score. The reaction time score could range from 0–5 (with higher values reflecting faster performance) based on the child's median reaction time for their correct responses to incongruent trials within defined thresholds. Reaction times were only included if they were equal to or above 100 ms and were no larger than three standard deviations away from the child's mean. For participants who failed to reach the 80% accuracy criterion, their computed score only reflected their accuracy scores. We examined both raw accuracy scores and computed scores within our analysis. Software errors meant that raw scores were not able to be generated for one participant and computed scores for three participants although their actigraphy data was included within the analysis.

Activity was determined during the Flanker task as mean movement from 2–5 minutes from task-onset to capture activity during the "Fish block" as the main cognitive test phase. Twenty-one children completed the Flanker task prior to 5-minutes, but their data was included if they were able to provide Actigraph data from 2–4 minutes, which they all were able to.

The impossibly perfect circles task

Motor activity was also assessed during an emotionally challenging task called the Impossibly Perfect Circles task (IPC),a task that is part of the Infant Laboratory Assessment Battery (Lab TAB) and which aims to elicit frustration or distress from the child in response to negative adult feedback (Goldsmith & Rothbart, 1996). The Lab-TAB includes standardized tasks that are intended to elicit a variety of emotions, can be scored at varying levels, and have been used successfully in developmental research interested in child temperament (Gagne et al., 2011).In particular, behaviours observed during this task have been used to measure stress reactivity (Winiarski et al., 2018) and emotion regulation (Landis et al., 2021).The IPC procedure involved the child being seated at a table and asked to draw a perfect green circle. After each circle that the child draws, the researcher critiques that circle (e.g., "That one is not round enough," "That is not quite right") and asks the child to draw another circle in a neutral voice. At every minute interval, the researcher repeated the instruction to draw a perfect green circle. The task lasted for 3½ minutes and activity was determined as the mean movement during this task phase. After the final circle was drawn the researcher gave the child positive feedback and praised the child's efforts for one-minute, but this additional period was not included in the analysis of motor activity.

Data analysis

To assess the relationship between rated ADHD symptoms and actigraphy hyperactivity across differing task conditions, Pearson's correlations were run between SDQ Inattention/hyperactivity scores (and the independent dimensions) and measured mean activity levels during the baseline condition, Flanker task, and IPC task. We investigated whether low executive function performance was linked with measured hyperactivity by running Pearson's correlations between Flanker task scores (raw and computed score) and measured mean activity levels during each task. We lastly conducted a moderated hierarchical regression analysis to examine whether the expected relationship between Flanker task performance and measured activity levels was moderated by symptom severity, as measured by rated SDQ hyperactivity scores.All analyses were run in IBM SPSS Statistics (version 25) and the moderation analysis was run using PROCESS (version 3.4; Hayes, 2017).

Results

Table 1 displays descriptive information for actigraphy movement data, SDQ scores and Flanker task performance. Greater mean movement activity was observed during the Flanker task compared to the baseline,Mean Difference (MD) = .80, SD = 3.69, t (94) = 2.10, $p = .04$, and IPC task, MD = 1.04, SD = 3.68, t (85) = 2.63, $p = .01$. There was no difference in activity during the baseline and IPC task. Table 2 illustrates the relationships between mean movement activity with SDQ ratings and Flanker task performance.

Objectively recorded and rated hyperactivity

Total SDQ inattention/hyperactivity scores were positively related with mean movement activity during the Flanker task, but not during the baseline condition or IPC task. This pattern of finding was specific to SDQ hyperactivity when the individual inattention and hyperactivity dimensions were examined respectively, as no relationships emerged between SDQ inattention scores and mean movement activity during any of the three different task conditions.

Additional analysis showed that children with the highest SDQ inattention/hyperactivity scores demonstrated the largest increase in hyperactivity from the baseline to the Flanker task (see Supplementary analysis).

Objectively measured hyperactivity and cognitive inhibition

Flanker task performance (both raw score and computed score) was inversely related with mean movement activity during the baseline and during the Flanker task.That is, higher scores on the Flanker task were associated with lower activity levels during the baseline and Flanker tasks respectively.No association emerged between Flanker task performance and mean movement activity during the IPC task.

Table 2. Pearson's correlations (r) between actigraphy mean movement activity and parent-rated strengths and difficulties questionnaire (SDQ) Inattention/hyperactivity scores, and Flanker task performance.

	Actigraphy movement activity		
	Baseline (n = 95)	Flanker task (n = 95)	Impossibly Perfect Circles task (n = 86)
SDQ			
Inattention/hyperactivity	.01	.22*	−.02
Hyperactivity	−.03	.23*	−.04
Inattention	.07	.14	.02
Flanker task			
Raw score	−.28**	−.36***	.04
Computed score	−.27*	−.37***	−.01

* $p < .05$, ** $p < .01$, *** $p < .001$, significant correlations are highlighted in bold

ADHD symptom severity as a moderator of objective hyperactivity and cognitive inhibition

We examined whether hyperactivity symptom severity moderated the relationship between Flanker task performance and measured activity levels during the Flanker task. We ran a moderated hierarchical regression analysis predicting mean movement activity during the Flanker task, entering both Flanker task performance (computed score) and SDQ Hyperactivity scores as centered predictor variables at Step 1, before entering the interaction term between these variables at Step 2. At Step 1, both Flanker task performance (inversely) and SDQ Hyperactivity scores (positively) uniquely predicted mean movement activity during the Flanker task (see Table 3). The interaction between Flanker task performance (computed score) and SDQ Hyperactivity scores was then entered at Step 2 (see Table 3), and was significant, and this interaction term accounted for an increase in the proportion of variance for mean movement activity above both variables independently.This interaction was probed further by exploring the effect of Flanker task performance on movement activity at different levels of SDQ Hyperactivity scores, and the region of significance was calculated (Hayes, 2017). Flanker task performance was significantly inversely related to mean movement activity for children with high (+1 *SD*), $b = -1.16$, $SE = 0.25$, $t = -4.46$, $p < .001$, and mean levels of SDQ Hyperactivity scores, $b = -0.64$, $SE = 0.20$, $t = -3.19$, $p < .01$, but not for children with low SDQ Hyperactivity scores (−1 *SD*), $b = -0.16$, $SE = 0.32$, $t = -0.49$, $p = .62$ (see Figure 1). The region of significance suggested that the association between Flanker task performance and mean movement activity shifted to a significant inverse relationship as SDQ hyperactivity scores increased beyond a score of 3.56.This analysis indicated that SDQ hyperactivity was a moderator of the relationship between Flanker task performance and objectively recorded activity, as this association was strongest as SDQ hyperactivity scores increased and was not evident for children with low SDQ hyperactivity scores.

The findings from the moderation analysis were further supported by a complementary analysis exploring the relationship betweenFlanker task performance and measured activity level across three defined SDQ groups (low, mean, and high) which were similar to those used in the moderation analysis (see Supplementary analysis). We found that measured hyperactivity during the Flanker task was only significantly related to lower Flanker performance in the high SDQ hyperactivity group, with no significant relationships emerging in the low or mean SDQ groups (see Supplementary Table S1).

Table 3. Moderated hierarchical regression analysis model predicting mean movement activity during the Flanker task from SDQ Hyperactivity scores and Flanker task performance.

	b	SE	β	t	p	df	R^2	F	p
Step 1						2, 89	.18	9.63	< .001
SDQ Hyperactivity	0.44	0.21	.21	2.13	.036				
Flanker score	−0.75	0.20	−.36	−3.72	<.001				
Step 2						3, 88	.23	8.61	< .001
SDQ Hyperactivity	0.43	0.20	.20	2.13	.036				
Flanker score	−0.65	0.20	−.31	−3.25	.002				
SDQ Hyperactivity x Flanker score	−0.27	0.11	−.23	−2.36	.021				

Flanker computed score was used for Flanker score. The change at Step 2 demonstrated an increase in explained variance, $\Delta R^2 = .05$, $\Delta F(1,88) = 5.57$, $p = .02$.

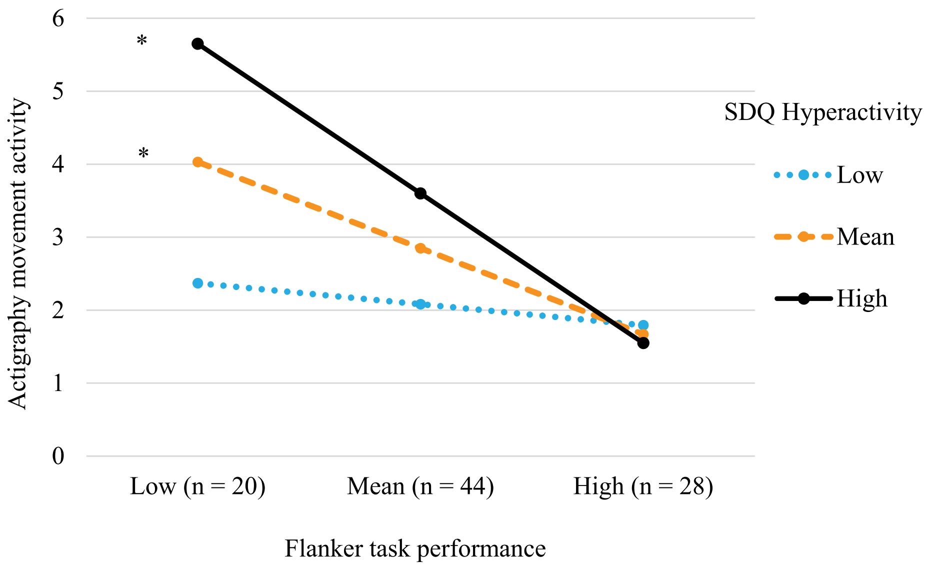

Figure 1. The relationship between actigraphy mean movement during the Flanker task and Flanker task performance across varying levels of SDQ Hyperactivity scores. Separate lines reflect low, mean and high levels of SDQ Hyperactivity scores based on ± 1 SD from the sample mean. * $p < .05$. Higher Flanker scores reflect better.

Discussion

The current study investigated within a sample of children (aged 5–7 years old) with emerging mental health problems, including ADHD symptoms, first, the relationship between behavioral ratings of ADHD and objectively recorded activity under varying environmental task conditions; and second, whether cognitive inhibition deficits are linked to excessive measured activity levels, and whether ADHD symptom severity moderated this association. In line with our expectation, we found that parent ratings of ADHD, driven by hyperactivity symptoms, were associated with objectively measured activity levels. This relationship between rated and objectively measured hyperactivity in young children was consistent with previous research conducted in older children within a population-based sample (Brocki et al., 2010) and a diagnosis of ADHD (Kofler et al., 2016), and supports the conceptual similarity of hyperactivity in young children without a diagnosis to the ADHD phenotype. This encourages the investigation of hyperactivity as a transdiagnostic dimension that exists prior to (and extends beyond) diagnostic classifications of ADHD. The specificity of the observed relationship between actigraphy-measured activity levels and parent-reported hyperactivity (in comparison to the absence of a relationship with inattention problems), further highlights the importance of examining hyperactivity as a distinct dimension.

The current study also identified that the association between rated and objectively recorded hyperactivity was specific to activity measured during the cognitive inhibition task, with no associations emerging for locomotion recorded during the baseline or emotional task conditions. This supports the contention that hyperactivity is not a ubiquitous symptom ofADHD, but rather that hyperactivity emerges in response to specific environmental task demands (Kofler et al., 2016). The absence of a relationship between rated and measured activity levels during the emotionally frustrating task suggests that hyperactivity within children does not reflect abnormal emotional processes, despite previously identified associations between ADHD symptomatology and deficient emotional reactivity and regulation including reduced frustration tolerance (Faraone et al., 2019; Seymour et al., 2019). The current findings suggest that young children at risk of ADHD do not demonstrate consistently elevated motor activity, but that hyperactive behavior emerges during cognitive challenges that place a high demand on their executive functioning capacities.

Furthermore, as expected, impaired performance on the cognitive inhibition task was linked with increased objective activity levels during the task, and this relationship emerged and strengthened as children's symptom severity increased (based on parent rated hyperactivity scores). Taken in combination, these results support an underlying association between deficient executive functioning and hyperactivity, and are consistent with theoretical perspectives that have proposed that excessive motor activity in ADHDis a by-product of core inhibitory deficits; excessive activity may reflect wider response inhibition difficulties important for self-control and regulation (Barkley, 1997), and/or a stimulation strategy intended to reduce the aversive nature of waiting for a reward due to a motivational style that struggles with delay aversion (Sonuga-Barke, 2002).

We also observed that impaired performance on the cognitive inhibition task was related to greater measured activity levels during the baseline task condition. Kofler et al. (2016) similarly reported that ADHD-related hyperactivity was greater in low stimulation conditions compared to mixed or high stimulation environments. This suggests that environments with low levels of distraction or stimulation – contrary to commonly recommended classroom-based approaches – may exacerbate hyperactivity in children at risk of ADHD. This is consistent with the optimal stimulation view of hyperactive behavior that proposes that children with high stimulation thresholds exhibit hyperactivity in situations where they are experiencing insufficient sensory stimulation (Zentall & Zentall, 1983). Kofler et al. (2016) further defined that ADHD-related hyperactivity is most evident under environmental conditions that combined high cognitive demands and low external stimulation, which may explain why the current study identified the relationship between cognitive inhibition impairments and increased motor activity under the baseline (low stimulation) and Flanker (high cognitive demand) task conditions respectively. This highlights the importance of considering the settings and task conditions under which activity levels are measured.Interestingly, additional analyses (reported in the Supplementary materials) indicated that the relationship between impaired performance on the cognitive inhibition task and measured hyperactivity during the baseline task condition was specific to children with average levels of symptoms (i.e., the mean SDQ group) and was not observed in the high SDQ group, which is surprising given that these children are most at risk of ADHD difficulties. It is also unclear why behavioral ratings of hyperactivity did not show a relationship with objective activity levels during the baseline task, although this may suggest that behavioral ratings of hyperactivity are tapping into different aspects of the ADHD phenotype than hyperactivity during cognitive inhibition performance.

Implications

Our findings highlight that it is important that individuals working closely with children with hyperactivity difficulties (e.g., teachers) may need to accommodate for an increase in movement during tasks that are cognitively demanding. Indeed, hyperactivity may serve a functional role in facilitating neurocognitive functioning in children with ADHD; Sarver et al. (2015) found that higher rates of gross motor activity were associated with better working memory performance in children (aged 8–12 years old) with a diagnosis of ADHD. In contrast, hyperactivity was associated with poorer working memory performance for children without ADHD. Individuals who therefore work with children at risk of hyperactivity may need to exercise caution in overcorrecting motor activity as it may be serving a function to augment executive function performance. Sarver and colleagues also proposed that non-disruptive devices or techniques could be incorporated into the classroom to facilitate movement that benefits academic task performance. A better understanding of the processes that underlie children's hyperactive behavior will ultimately inform more individualized and targeted interventions.

Limitations

The current study did not measure activity levels during other types of executive function tasks and so the association between hyperactivity and impaired cognitive inhibition may reflect wider attentional or executive function deficiencies than specifically disinhibition (Alderson et al., 2012; Kofler et al., 2016; Patros et al., 2017). In addition, the current research design did not enable us to determine the direction of causality, i.e., whether executive function impairments caused hyperactivity or whether increased activity led to poorer cognitive inhibition performance. Regardless, the current results support the notion of an underlying association between measured on-task hyperactivity and deficient executive functioning in young children, and this relationship was most evident in children rated with high hyperactive behavioral difficulties.

The relationships between rated and objective activity levels were modest in the current developmental sample compared to associations previously identified in clinical populations (Rapport et al., 2006). Weaker associations between rated and objectively recorded activity levels may be expected in samples where levels of hyperactivity are low or more typical (Brocki et al., 2010) and in those with only emerging difficulties.

We only examined parent-informant behavioral ratings of ADHD symptoms, which may predominantly reflect hyperactivity levels within the home. It is possible that a different pattern of relationships between rated and observed behaviors would have been observed if ADHD symptoms had been rated by other informants, who would have captured hyperactivity in other contexts. For example, school-teacher's ratings of hyperactivity may reflect children's activity levels in structured cognitive contexts to a greater degree and this could have led to a stronger relationship between rated and observed hyperactivity during the Flanker task than the current association that was identified.

TheFlanker task was not fully adaptive to each child's individual performance and therefore may have exerted different executive function demands on children. This varying demand may have minimized the level of activity measured amongst children who experienced lower cognitive demand – according to an inhibition model of ADHD (where excessive motor activity in ADHD is a by-product of core inhibitory deficits [Barkley, 1997; Sonuga-Barke, 2002]) -and may therefore have led to an underestimation of the association between executive function performance and measured activity levels. We note, however, that the Flanker task scores obtained in the current study indicated that the task was challenging overall.

The current study measured the activity of the children through placement of the actigraphy on the sternum and it is possible that we could have obtained different findings if we had used an alternative measurement site (e.g., hand, ankle). However, there is evidence that when it comes to measuring activity levels in children it is best to stay close to the mass center of the body (Konstabel et al., 2019) and that chest-worn accelerometers are better than wrist-worn ones for measuring movement (Zhang et al., 2016). In addition, many children with neurodevelopment difficulties have difficulties tolerating an actigraphy device on their wrist and for them an alternative (and more discreet) placement of the device is needed (Adkins et al., 2012). Similarly, due to concerns regarding what the children would tolerate, the current study measured activity using an accelerometer-based heart monitor for only a short period (approximately 20 minutes), in contrast to studies that used ambulatory monitoring of activity over longer and more continuous periods (e.g., Porrino et al., 1983). The shorter procedure that we adopted allowed us to capture objective activity data across a range of experimental tasks for most of the sample.

Finally, we note that this study was not preregistered and therefore the analyses were exploratory and need replication.

Conclusion

The current findings show that behavioral ratings of hyperactivity in young children aged 4–7 years at-risk for mental health difficulties were reflected in actigraphy-measured hyperactive behavior,supporting the use of objective measures of activity levels to index the ADHD phenotype prior to diagnosis. This relationship was specifically demonstrated during a cognitive inhibition task that placed a high demand on the children's executive functioning capacities. Impaired cognitive inhibition performance was also related to objectively recorded hyperactivity levels and this association was strongest in children rated as having the highest levels of hyperactive behavior. These findings support an underlying association between hyperactivity and impaired executive functioning and indicate that hyperactivity in young children at risk of ADHD is not a ubiquitous symptom, but rather emerges in response to environmental (in this case, cognitive) demands. These results highlight the need for further research into the role of hyperactivity as a transdiagnostic dimension in children's neurodevelopmental problems.

Acknowledgments

We are extremely grateful to the children, families and schools that took part in our research. We would like to thank Christopher Hobson, Rosanna Stenner, Angie Wigford, Holly Howe-Davies, Dolapo Adegboye, Claire Bowsher-Murray, Kate Anning, Eleri Jones, Katie Larkins, Louise Page, Bea Acworth, Ella Watson, Zoey Smith, Olivia Gallen, Lowri Adams, Judith Ogunkoya, Ffion Williams, George Metaxa, Jessica Brown, Lucie Mathison, and SiânLavis for their assistance with this study and their help with recruitment.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by The Waterloo Foundation [grant number 511633] awarded to SHMvG.

References

Adkins, K. W., Goldman, S. E., Fawkes, D., Surdyka, K., Wang, L., Song, Y., & Malow, B. A. (2012). A pilot study of shoulder placement for actigraphy in children. *Behavioral Sleep Medicine*, *10*(2), 138–147. https://doi.org/10.1080/15402002.2011.596598

Alderson, R. M., Rapport, M. D., Kasper, L. J., Sarver, D. E., & Kofler, M. J. (2012). Hyperactivity in boys with attention deficit/hyperactivity disorder (ADHD): The association between deficient behavioral inhibition, attentional processes, and objectively measured activity. *Child Neuropsychology*, *18*(5), 487–505. https://doi.org/10.1080/09297049.2011.631905

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders (DSM-5®)*. American Psychiatric Publishing.

Arnett, A. B., MacDonald, B., & Pennington, B. F. (2013). Cognitive and behavioral indicators of ADHD symptoms prior to school age. *Journal of Child Psychology and Psychiatry*, *54*(12), 1284–1294. https://doi.org/10.1111/jcpp.12104

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin*, *121*(1), 65–94. https://doi.org/10.1037/0033-2909.121.1.65

Becker, A., Woerner, W., Hasselhorn, M., Banaschewski, T., & Rothenberger, A. (2004). Validation of the parent and teacher SDQ in a clinical sample. *European Child &Adolescent Psychiatry*, *13*(2), 11–16. https://doi.org/10.1007/s00787-004-2003-5

Berlin, L., & Bohlin, G. (2002). Response inhibition, hyperactivity, and conduct problems among preschool children. *Journal of Clinical Child and Adolescent Psychology*, *31*(2), 242–251. https://doi.org/10.1207/s15374424jccp3102_09

Berlin, L., Bohlin, G., Nyberg, L., & Janols, L.-O. (2004). How well do measures of inhibition and other executive functions discriminate between children with ADHD and controls? *Child Neuropsychology*, *10*(1), 1–13. https://doi.org/10.1076/chin.10.1.1.26243

Booth, J. R., Burman, D. D., Meyer, J. R., Lei, Z., Trommer, B. L., Davenport, N. D., Li, W., Parrish, T. B., Gitelman, D. R., & Marsel Mesulam, M. (2005). Larger deficits in brain networks for response inhibition than for visual selective attention in attention deficit hyperactivity disorder (ADHD). *Journal of Child Psychology and Psychiatry*, *46*(1), 94–111. https://doi.org/10.1111/j.1469-7610.2004.00337.x

Brocki, K. C., Tillman, C. M., & Bohlin, G. (2010). CPT performance, motor activity, and continuous relations to ADHD symptom domains: A developmental study. *European Journal of Developmental Psychology*, *7*(2), 178–197. https://doi.org/10.1080/17405620801937764

Cheung, C. H., Rijsdijk, F., McLoughlin, G., Brandeis, D., Banaschewski, T., Asherson, P., & Kuntsi, J. (2016). Cognitive and neurophysiological markers of ADHD persistence and remission. *The British Journal of Psychiatry*, *208*(6), 548–555. https://doi.org/10.1192/bjp.bp.114.145185

Dekkers, T. J., Rapport, M. D., Calub, C. A., Eckrich, S. J., & Irurita, C. (2021). ADHD and hyperactivity: The influence of cognitive processing demands on gross motor activity level in children. *Child Neuropsychology*, *27*(1), 63–82. https://doi.org/10.1080/09297049.2020.1793924

Erskine, H. E., Norman, R. E., Ferrari, A. J., Chan, G. C., Copeland, W. E., Whiteford, H. A., & Scott, J. G. (2016). Long-term outcomes of attention-deficit/hyperactivity disorder and conduct disorder: A systematic review and meta-analysis. *Journal of the American Academy of Child and Adolescent Psychiatry*, *55*(10), 841–850. https://doi.org/10.1016/j.jaac.2016.06.016

Fair, D. A., Bathula, D., Nikolas, M. A., & Nigg, J. T. (2012). Distinct neuropsychological subgroups in typically developing youth inform heterogeneity in children with ADHD. *Proceedings of the National Academy of Sciences*, *109*(17), 6769–6774. https://doi.org/10.1073/pnas.1115365109

Faraone, S. V., Rostain, A. L., Blader, J., Busch, B., Childress, A. C., Connor, D. F., & Newcorn, J. H. (2019). Practitioner review: Emotional dysregulation in attention-deficit/hyperactivity disorder–implications for clinical recognition and intervention. *Journal of Child Psychology and Psychiatry*, *60*(2), 133–150. https://doi.org/10.1111/jcpp.12899

Gagne, J. R., Van Hulle, C. A., Aksan, N., Essex, M. J., & Goldsmith, H. H. (2011). Deriving childhood temperament measures from emotion-eliciting behavioral episodes: Scale construction and initial validation. *Psychological Assessment*, *23*(2), 337–353. https://doi.org/10.1037/a0021746

Goldsmith, H., & Rothbart, M. (1996). *The laboratory temperament assessment battery (LabTAB): Locomotor version 3.0 technical manual*. Department of Psychology, University of Wisconsin.

Goodman, R. (1997). The strengths and difficulties questionnaire: a research note. *Journal of Child Psychol Psychiatry, 38*(5),581–586. https://doi.org/10.1111/j.1469-7610.1997.tb01545.x

Hayes, A. F. (2017). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach*. Guilford Publications.

Kofler, M. J., Raiker, J. S., Sarver, D. E., Wells, E. L., & Soto, E. F. (2016). Is hyperactivity ubiquitous in ADHD or dependent on environmental demands? Evidence from meta-analysis. *Clinical Psychology Review*, *46*, 12–24. https://doi.org/10.1016/j.cpr.2016.04.004

Konrad, K., Gauggel, S., Manz, A., & Schöll, M. (2000). Inhibitory control in children with traumatic brain injury (TBI) and children with attention deficit/hyperactivity disorder (ADHD). *Brain Injury*, *14*(10), 859–875. https://doi.org/10.1080/026990500445691

Konstabel, K., Chopra, S., Ojiambo, R., Muñiz-Pardos, B., & Pitsiladis, Y. (2019). Accelerometry-based physical activity assessment for children and adolescents. In K. Bammann, L. Ler, I. Pigeot, & W. Ahrens (Eds.), *Instruments for health surveys in children and adolescents* (pp. 135–173). Springer.

Landis, T. D., Garcia, A. M., Hart, K. C., & Graziano, P. A. (2021). Differentiating Symptoms of ADHD in Preschoolers: The Role of Emotion Regulation and Executive Function. *Journal of Attention Disorders*, *25*(9),1260–1271. https://doi.org/10.1177/1087054719896858

Murillo, L. G., Cortese, S., Anderson, D., Di Martino, A., & Castellanos, F. X. (2015). Locomotor activity measures in the diagnosis of attention deficit hyperactivity disorder: Meta-analyses and new findings. *Journal of Neuroscience Methods*, *252*, 14–26. https://doi.org/10.1016/j.jneumeth.2015.03.001

Musser, E. D., & Raiker, J. S., Jr. (2019). Attention-deficit/hyperactivity disorder: An integrated developmental psychopathology and research domain criteria (RDoC) approach. *Comprehensive Psychiatry*, *90*, 65–72. https://doi.org/10.1016/j.comppsych.2018.12.016

Patros, C. H., Alderson, R. M., Hudec, K. L., Tarle, S. J., & Lea, S. E. (2017). Hyperactivity in boys with attention-deficit/hyperactivity disorder: The influence of underlying visuospatial working memory and self-control processes. *Journal of Experimental Child Psychology*, *154*, 1–12. https://doi.org/10.1016/j.jecp.2016.09.008

Porrino, L. J., Rapoport, J. L., Behar, D., Sceery, W., Ismond, D. R., & Bunney, W. E. (1983). A naturalistic assessment of the motor activity of hyperactive boys: I. Comparison with normal controls. *Archives of General Psychiatry*, *40*(6), 681–687. https://doi.org/10.1001/archpsyc.1983.04390010091012

Rapport, M. D., Kofler, M. J., & Himmerich, C. (2006). Activity measurement. In Michel Hersen (Ed.), *Clinician's handbook of child behavioral assessment* (pp. 125–158). Elsevier.

Sarver, D. E., Rapport, M. D., Kofler, M. J., Raiker, J. S., & Friedman, L. M. (2015). Hyperactivity in attention-deficit/hyperactivity disorder (ADHD): Impairing deficit or compensatory behavior? *Journal of Abnormal Child Psychology*, *43*(7), 1219–1232. https://doi.org/10.1007/s10802-015-0011-1

Sax, L., & Kautz, K. J. (2003). Who first suggests the diagnosis of attention-deficit/hyperactivity disorder? *The Annals of Family Medicine*, *1*(3), 171–174. https://doi.org/10.1370/afm.3

Seymour, K. E., Macatee, R., & Chronis-Tuscano, A. (2019). Frustration tolerance in youth with ADHD. *Journal of Attention Disorders*, *23*(11), 1229–1239. https://doi.org/10.1177/1087054716653216

Sonuga-Barke, E. J. (2002). Psychological heterogeneity in AD/HD—a dual pathway model of behaviour and cognition. *Behavioural Brain Research*, *130*(1–2), 29–36. https://doi.org/10.1016/S0166-4328(01)00432-6

Thomas, R., Sanders, S., Doust, J., Beller, E., & Glasziou, P. (2015). Prevalence of attention-deficit/hyperactivity disorder: A systematic review and meta-analysis. *Pediatrics*, *135*(4), e994–e1001. https://doi.org/10.1542/peds.2014-3482

Visser, S. N., Danielson, M. L., Bitsko, R. H., Holbrook, J. R., Kogan, M. D., Ghandour, R. M., Perou, R., & Blumberg, S. J. (2014). Trends in the parent-report of health care provider-diagnosed and medicated attention-deficit/hyperactivity disorder: United States, 2003–2011. *Journal of the American Academy of Child and Adolescent Psychiatry*, *53*(1), 34–46. e32. https://doi.org/10.1016/j.jaac.2013.09.001

Winiarski, D. A., Engel, M. L., Karnik, N. S., & Brennan, P. A. (2018). Early life stress and childhood aggression: Mediating and moderating effects of child callousness and stress reactivity. *Child Psychiatry and Human Development*, *49*(5), 730–739. https://doi.org/10.1007/s10578-018-0785-9

Zelazo, P. D., Anderson, J. E., Richler, J., Wallner-Allen, K., Beaumont, J. L., & Weintraub, S. (2013). II. NIH toolbox cognition battery (CB): Measuring executive function and attention. *Monographs of the Society for Research in Child Development*, *78*(4), 16–33. https://doi.org/10.1111/mono.12032

Zentall, S. S., & Zentall, T. R. (1983). Optimal stimulation: A model of disordered activity and performance in normal and deviant children. *Psychological Bulletin*, *94*(3), 446–471. https://doi.org/10.1037/0033-2909.94.3.446

Zhang, J. H., Macfarlane, D. J., & Sobko, T. (2016). Feasibility of a chest-worn accelerometer for physical activity measurement. *Journal of Science and Medicine in Sport*, *19*(12), 1015–1019. https://doi.org/10.1016/j.jsams.2016.03.004