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Measuring Children's Behavioral Regulation in the Preschool Classroom: An Objective, Sensor-Based Approach

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Abstract

Children's abilities to regulate their behaviors are critical for learning and development, yet researchers lack an objective, precise method for assessing children's behavioral regulation in their everyday environments such as their classrooms. This study tested a sensor-based approach to assess preschool children's behavioral regulation objectively, precisely, and naturalistically. Children wore accelerometer devices as they engaged in center-based play in their preschool classrooms for roughly 45 minutes ($N = 50$ children, 48% female, mean age = 4.5 years). Set to record data each second, these devices collected information about children's movement ($N = 140{,}564$ observations). From these data, the authors extracted concrete behaviors hypothesized to index behavioral regulation and compared them with teacher and observer ratings of the same. Initiating movement more frequently, staying seated in activities for shorter amounts of time, and spending a greater amount of time in motion were related to lower ratings of attention and inhibitory control by teachers and by observers of classroom group time, median $r = .45$, $p < .01$. These same objectively measured behaviors showed only weak associations with children's performance on assessments of cognitive regulation, median $r = .11$, $p = .47$. The findings indicate that ambulatory accelerometers can capture movement-based indicators of children's behavioral regulation in the classroom setting and that performance on measures of cognitive regulation does not strongly predict children's behavior in the classroom. As an unobtrusive and objective measure, actigraphy may become an important tool for studying children's behavioral regulation in everyday contexts.

Learning to regulate one's behavior is a fundamental task for all children. Despite the importance of behavioral regulation, methods to assess it in the real-world face challenges related to subjectivity and inter-rater agreement. These limitations hinder the understanding of children's self-regulation in the everyday contexts where children develop it (McClelland & Cameron, 2012). One possible way to overcome such limitations is to employ wearable

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sensors to observe behavior objectively and naturalistically (Trull & Ebner-Priemer, 2014). The goal of this study was to explore the utility of wearable accelerometers for assessing young children's behavioral regulation in preschool classrooms. In validating this approach against existing measures of children's cognitive and behavioral regulation, we also provide a test of the hypothesis that young children's cognitive regulation is empirically distinct from their behavioral regulation.

Self-Regulation in Early Childhood

Children's behavioral regulation is part of their self-regulation, an umbrella construct that describes the processes by which individuals maintain deliberate control of their thoughts, behaviors, and emotions (Nigg, 2017). Self-regulation is foundational for school readiness (Blair & Raver, 2015) and predicts later academic success and social adjustment (Robson et al., 2020). Early in life, children rely on adult caregivers to regulate their emotions and behaviors and, over the course of early childhood, gradually develop the ability to regulate themselves (Cox et al., 2010; Sameroff, 2010). Although maturation of these skills is not complete until adulthood, these capacities develop rapidly during the preschool years (ages 3-5), making it a foundational period for the development of self-regulation and a critical period to understand (Best & Miller, 2010).

Psychologists have generally approached the study of self-regulation in one of two ways. A cognitive-focused approach examines the executive mental processes that support enacting controlled, deliberate responses, processes known as executive functions (Blair, 2016; Diamond, 2013). Other researchers have approached the study of self-regulation from a perspective of temperament, with an emphasis on innate aspects of reactivity in "motor, affective, and sensory response systems" (Rothbart et al., 2001, p. 1395) and the intentional modulation of this reactivity known as "effortful control" (Liew et al., 2019). Many scholars have noted the conceptual overlap between the constructs of executive function, effortful control, and self-regulation (Bailey & Jones, 2019; Gagne, 2017; Liew, 2012) as well as the inconsistency with which scholars use terms or apply concepts when studying self-regulation (Jones et al., 2016; Morrison & Grammer, 2016).

To make sense of these differences, Nigg (2017) proposed an integrative framework for conceptualizing regulation, which he defined as the "ongoing, dynamic, and adaptive modulation of an internal state (emotion, cognition) or behavior" (Nigg, 2017, p. 361). In this framework, regulation is made up both of internal processes for regulation of the self as well as external influences from one's environment. Consistent with other work (Cole et al., 2019; Liew et al., 2019; Ursache et al., 2012), self-regulation in Nigg's (2017) model emerges from two internal processes, namely, the reactive, "bottom-up" process of arousal and the and the effortful, "top-down" process of control, which influence one another dynamically. Conceptually, one's abilities to regulate thoughts, behaviors, and emotions are thought to be separable but inter-related (Bailey & Jones, 2019) and emerge from an integrated construct of regulation (Nigg, 2017). Despite conceptual similarities, however, dimensions of cognitive and behavioral regulation frequently demonstrate low empirical associations (Toplak et al., 2013).

More research is needed to understand how similar or dissimilar cognitive and behavioral dimensions of self-regulation are. Such a distinction has been difficult to draw in many studies because the commonly used assessments of cognitive regulation (i.e., direct assessments) and behavioral regulation (i.e., adult reports) also differ on the important dimension of objectivity (McCoy, 2019). Though researchers have separated dimensions of cognitive and behavioral regulation in factor analytic work on performance-based assessments (Lin et al., 2019; Montroy et al., 2019), the extent to which this distinction holds in everyday settings such as the classroom is currently unclear. Having an objective measure of children's behavioral regulation in the classroom context could shed light on this empirical question. Such a tool would also benefit applied research. Because children's behavioral regulation plays an important role in the classroom context and in children's development more broadly, educators and policymakers increasingly seek to support these aspects of children's behavioral regulation in the classroom context (e.g., Office of Head Start, 2019), but efforts are hindered by a lack of appropriate tools to measure these behaviors in classroom settings.

Current Approaches to Measuring Behavioral Regulation

The measurement of children's behavioral regulation is complicated by the fact that regulation is an internal process that researchers cannot directly observe (Nigg, 2017). Instead, researchers must make inferences about regulation based on observed behaviors. One way that researchers generate confidence in such inferences is to use a structured task in which the responses from participants clearly indicate the engagement of a controlled response rather than an automatic or uncontrolled response. One example is the Marshmallow task in which children are instructed to wait for a desirable treat in order to receive more of it later (Mischel et al., 1989). However, such tasks, by their nature, do not provide information about behavior in the classroom but about children's behavior in a research setting. Though the assessments are standardized and internally valid, they have limited external validity if the goal is to understand children's behavior among peers and in the face of competing distractions in the classroom context (Jones et al., 2016). Understanding how children behave in such real-world situations is vital for intervention efforts (McClelland & Cameron, 2012).

One way that researchers assess children's everyday behavioral regulation is to present teachers and parents with statements describing regulated or dysregulated behavior and ask how true the statement is for particular children (McCoy, 2019). The validity of these questionnaires relies on the logic that overt behaviors can provide insight about the internal process of regulation. One of the most observable aspects of children's behavior is their physical, gross motor movement (Kofler et al., 2020). This fact is reflected in the content of questionnaire items that describe children's behavioral regulation, namely their attention (i.e., the ability to sustain focus and ignore distractions; Bailey & Jones, 2019) and inhibitory control (i.e., the ability to inhibit an inappropriate or automatic response and enact a required one; McCoy, 2019). For example, the Children's Behavior Questionnaire (CBQ; Rothbart et al., 2001) is a widely used measure of children's behavioral regulation and uses the following description as an item to assess attention (reverse-coded): *"[this child] will move from one task to another without completing any of them"* and the following description as an item assessing inhibitory control: *"[this child] can wait before entering into new activities if s/he is asked to."*

Although they provide information about children's behavior in everyday contexts, such teacher or parent ratings are subjective and only give information about children's behavior generally rather than about specific points in time; they can also be influenced by the rater's relationship with the child (McCoy, 2019). Observational approaches can achieve objective measurement naturalistically (McCoy et al., 2017), but they present other major challenges. To reduce subjectivity, the researcher must develop detailed protocols to codify and interpret ambiguous behavioral cues, train a team of coders to interpret them the same way, and then code (or, ideally, double-code) observations (Ostrov & Hart, 2013). These same checks that reduce subjectivity introduce costs in time and resources. Even then, the researcher must define an acceptable level of inter-rater unreliability, which reduces precision (Shrout & Fleiss, 1979). Because they are time-intensive, observations are typically short, tapping just a snapshot of children's behavior that may not be representative of their behavior more generally. Thus, current approaches to measuring children's behavioral regulation are either rigorous but have limited real-world significance or achieve real-world significance at the cost of measurement precision. As a result, researchers lack an objective, precise way to measure children's behavioral regulation naturalistically. Because many behaviors thought to indicate behavioral regulation in early childhood involve physical movement (or the lack of it; Rothbart et al., 2001), we propose that actigraphy, the measurement of human movement and activity, can reliably index aspects of children's behavioral regulation in the real world.

Actigraphy as a Measure of Behavior

Actigraphy has been used for decades to study human movement (e.g. Brown et al., 1990), including in studies of children's physical activity (Freedson et al., 1997) and sleep (Sadeh & Acebo, 2002). Actigraphy has also long been used to show differences in mean activity levels between children diagnosed with ADHD and those without it (Dane et al., 2000) and to study changes in behavior following pharmacological treatment for ADHD (for a review see De Crescenzo et al., 2014). Other studies have found that accelerometers show validity in distinguishing between children with and without ADHD in terms of how frequently they move, how much they move, and how consistently they move (Kam et al., 2010; Wood et al., 2009). More recently, a study demonstrated that children's objectively assessed physical activity predicted their inattentive and hyperactive/impulsive behaviors both concurrently and longitudinally in a population-representative cohort of children in the U.K. (Brandt et al., 2021). This finding suggests that actigraphy can capture indicators of behavioral regulation in non-clinical samples.

Accelerometers are one device for measuring actigraphy and they have strong measurement properties. Accelerometers record the wearer's amount of physical movement as activity counts in fine-grained detail and create an intensive time series of data (Freedson et al., 2005). The activity counts produced by these devices have been classified into levels of intensity of physical movement for preschoolers, allowing researchers to classify ranges of activity counts as indicating sedentary activity versus physical (i.e., "non-sedentary") activity (Butte et al., 2014; Pate et al., 2006). The automated, and thus objective, nature of accelerometers means they have high internal validity. They are unobtrusive and provide no feedback to participants and are thus an ideal data collection tool in naturalistic classroom settings.

The Current Study

The first aim of this study was to extract features from accelerometer data that could index behavioral regulation. We hypothesized that by measuring children's movement through actigraphy, we could capture distinct, quantifiable features that characterize children's behavioral regulation as they engaged in regular classroom activities. These hypothesized metrics have direct parallels to some of the overt behaviors described in questionnaire items that assess behavioral regulation (see Table 1). Indeed, children's motor reactivity and their modulation of it are key aspects of regulation that these items are designed to capture (Rothbart et al., 2001). The accelerometer metrics we used are 1) the number of times a child initiates movement (i.e., shifts from sedentary to non-sedentary activity); 2) the mean length of children's sedentary periods; and 3) the percentage of time a child spends in motion (i.e., in non-sedentary activity). Figure 1 illustrates how these three metrics can be extracted from accelerometer data, showing an annotated graph of a participant's cumulative physical activity over the period observed.

After identifying these quantifiable behaviors in children's accelerometer data, we then sought to examine the validity of these features for indexing aspects of children's behavioral regulation. Despite the limitations of the measurement approaches described above (i.e., adult ratings and observations), they are widely used and accepted measures of children's behavioral regulation (McCoy, 2019) and thus provide an essential validity check for the novel approach tested in this study. In the current study, we tested the validity of the accelerometer specifications of children's behavioral regulation against teacher ratings, direct observations of behavioral regulation, and direct assessments of cognitive regulation. Given the strong face validity of the accelerometer measures, we hypothesized that they would correlate with existing measures of children's behavioral regulation, but less strongly with measures of their cognitive regulation.

Methods

Participants

This study took place at a preschool in the southwest United States. A total of 50 children across five classrooms participated (48% female, mean age = 4.5 years). Children were eligible to participate in this study if they attended the school in the fall of 2019. The participants were 74% non-Hispanic White, 14% Hispanic White, and 12% either Black, Asian, or another race. The sample was affluent, with roughly two-thirds (63%) of children came from families earning more than $150,000 per year, a total roughly 1.5 times the median household income of $96,000 for 2019 in the surrounding census-designated metro statistical area.

Protocol

Children participating in the study wore small, lightweight devices with accelerometer technology to log the amount of activity they engaged in while at preschool. These devices (ActiGraph GT3X, Pensacola, FL) are widely used in studies of human activity and movement (Cain et al., 2013) and measure movement across axes on multiple planes. The device is lightweight and the size of a small matchbox. Each child's parent or classroom teacher attached the device comfortably around the child's waist, on their back, and over their clothes at the beginning of the school day. Placing the device around the waist allowed us to measure overall gross motor movement as opposed to only upper- or lower-body movement, as when devices are worn on the wrist or ankle. The device does not impede movement and has no interface providing feedback to participants or data collectors in the field. To minimize any novelty effect that could impact children's activity levels, we collected pilot data with the children over several days, allowing them to become accustomed to the devices, but excluded these data from analysis. The devices were set to record data in 1-second epochs. In this study, we analyzed data from roughly 45 minutes of the school day ($N = 140{,}564$ seconds) while children were engaged in play indoors at various classroom centers (e.g., blocks, puzzles, dramatic play, arts and crafts).

We chose to examine children's behavior during freeplay because we expected it to have the most natural variability in children's movement, as opposed to snack or classroom circle time, when children are expected to remain seated. Direct assessments with children were conducted one-on-one in a quiet area of the school building. Observations of children's behavior occurred during classroom circle time. Children's participation in wearing accelerometers, completing direct assessments, and classroom observations occurred on the same day. Teachers completed questionnaires when the children were not present at school.

Measures

Accelerometer-Derived Indicators of Behavioral Regulation—We hypothesized that ambulatory accelerometer data could reveal patterns of behavior that indicate children's behavioral regulation (see Figure 1). These patterns describe how much and how frequently children were moving versus remaining seated during center-based free play. To operationalize movement, we employed a commonly used activity cutoff to determine when a preschool child was sedentary or not, namely 200 activity counts per 15-seconds (Pate et al., 2006). Children were considered sedentary if their activity was below this cutoff and non-sedentary if their activity was above this cutoff. We extracted three features which summarize children's behavior during the period observed: 1) the number of times a child initiated movement (i.e., shifted from sedentary to non-sedentary activity; 2) the mean length of a child's sedentary periods (transformed using a natural log function to reduce skew prior to analysis); and 3) the percentage of time a child spent in movement (i.e., in non-sedentary activity) during the observation period.

Teacher-Rated Behavioral Regulation—Teachers provided global ratings of each child's overall levels of attention and inhibitory control. We selected five items from of both these domains in Rothbart and Putnam's (2006) *Children's Behavior Questionnaire*, retaining items relevant to the classroom setting. A sample item for attention was, "[this child,] when drawing or coloring in a book, shows strong concentration." A sample item for inhibitory control was, "[this child] can wait before entering into new activities if s/he is asked to." We adapted the scale to range from 1 "Not at all true" to 5 "Extremely true." Internal consistency was high for the attentional control (α = .87) and for inhibitory control subscales (α = .91).

Observed Classroom Behavioral Regulation—To understand how children regulated their behavior during regular classroom activities, we conducted observations using items adapted from the Regulation Related Skills Measure (RRSM; McCoy et al., 2017). This tool measures the frequency with which children demonstrate specific behaviors indicating inhibitory control and attention within the classroom setting. We adapted the measure to live coding because we could not secure the proper permissions to video record the whole classroom. To adapt the measure, we reduced the number of items to code to six. We chose three items that indicated behaviors related to *attentional control*: "child pays attention to the task at hand," "ignores distractions during an activity," and "shows evidence of listening." We also chose three items indicating behaviors related to *inhibitory control*: "child controls physical movements," "follows classroom rules and routines independently," and "inhibits inappropriate or automatic responses and enacts appropriate responses." Internal consistency was high for items capturing classroom-based inhibitory control (α = .89) and attention (α = .92). The items showed the same factor structure as the full RRSM, with separate subscales for inhibitory control and attention (Koepp et al., 2019). That is, a confirmatory factor analysis using Mplus 8 confirmed that a two-factor structure fit better than a one-factor structure in this sample ($p < .001$).

Trained graduate and undergraduate data collectors coded children's behavior during classroom circle time. A daily circle time is a routine activity in early childhood education in which the whole class gathers to engage in a lesson, listen to a story, or sing songs directed by the classroom teacher. Children are expected to remain seated in their spot, keep their hands to themselves, raise their hand before speaking, pay attention to the activity, and avoid engaging with their neighbors or objects in their surroundings. The concrete and standardized expectations during this period gave us confidence that we could interpret children's behaviors reliably. Two coders observed the behavior for each child during a 5-minute observation period, timed using stopwatches, and gave global ratings for each item for the period observed during a one-minute scoring period. Scores range from 1 to 4 with higher scores indicating more consistent displays of the behavior in the classroom context (1 = consistently does not, 2 = most of the time does not, 3 = does most of the time, 4 = does consistently). We assessed inter-rater reliability using intraclass correlations for the RRSM subscales (Shrout & Fleiss, 1979). The final inter-rater reliability weighted each coder's ICC according to the proportion of scores that they contributed. The ICCs were .73 for attentional control and .75 for inhibitory control.

Cognitive Regulation—We used two global assessments of children's cognitive regulation, the Head-Toes-Knees-Shoulder assessment (HTKS; Ponitz et al., 2009) and the Dimensional Change Card Sort (DCCS; Zelazo, 2006). During the HTKS assessment, children must enact a response that is the opposite of what an assessor prompts them to do, such as touching their toes when the assessor says to touch their head. Completing up to 30 rounds, children receive a score of 2 for a correct response, 1 for a self-corrected response, and 0 for an incorrect response. Thus, possible scores ranged from 0 to 60. In the DCCS, children sorted cards, first according to color and then according to shape (the "post-switch trial"). Children received a score of 1 for this assessment if they successfully completed the post-switch trial (that is, sorted 5 or more of the 6 cards correctly in this round), receiving a 0 otherwise. We assessed inter-rater reliability on roughly one-third (35%) of all the lab-based assessments using Cohen's kappa, a marker of agreement between raters that adjusts for expected agreement based on chance (Cohen, 1960). Reliability across raters was high for the Head, Toe, Knees, Shoulders task (κ = .88) and the Dimensional Change Card Sort (κ = .94).

Analysis

To examine the validity of the accelerometer specifications of behavioral regulation, we examined their bivariate correlations with the other measures of children's cognitive and behavioral regulation. We then used the accelerometer specifications to predict the other measures of cognitive and behavioral regulation in a regression framework to control for age, gender, classroom, and the amount of time children wore the accelerometers. We used OLS regression to predict all outcomes, except for successful completion of the DCCS post-switch trial, which we predicted using logistic regression. When predicting observer ratings of behavioral regulation, we also controlled for the type of circle time activity children engaged in (e.g., storytime, singing a song, lesson) and used robust standard errors to account for the skewed distribution.

Results

Descriptive statistics are presented in Table 2 and a correlation matrix is presented in Table 3. The preschool children in our sample initiated movement about 26 times, on average, during the roughly 45 minutes of center-based freeplay observed, *M* (SD) = 25.9 (14.6), range = 1 – 59. The mean length of their discrete sedentary periods was about two minutes, *M* (SD) = 127 (96) seconds, range = 20 – 402 seconds. Children were in motion for about one-fifth of the period observed, on average, *M* (SD) = 21.1% (13.7%), range = 4.7% - 57.2%.

Bivariate analyses showed statistically significant correlations between accelerometer-based measures of children's behavioral regulation and teacher ratings of attention and inhibitory control (CBQ), ranging in magnitude from *r*s = .29 to .55, *p*s < .05 to < .001, median $r = .41$, $p < .01$. The largest correlation observed was between the teacher ratings of attention and the number of times children initiated movement during indoor freeplay, $r = -.55$, $p < .001$. That is, children who initiated movement less frequently were rated by the teachers as having the highest attention control. The accelerometer specifications of behavioral regulation also showed correlations with observer ratings of children's attention and inhibitory control during classroom circle time (RRSM). Although not all were statistically significant, *r*s = .17 to .49, $p = .26$ to < .001, the median correlation with observer ratings across subscales was substantial, $r = .43$, $p < .01$.

The accelerometer-based specifications of behavioral regulation showed weak associations with the measures of cognitive regulation. They appeared to have no association with the HTKS, with correlations ranging in magnitude from $r = .01$ to .07, median $r = .02$, $p = .87$. They showed only weak associations with the DCCS, with correlations ranging in magnitude from $rs = .15$ to .17, median $r = .16$, $p = .26$.

Overall, the pattern of results held in regression models after accounting for children's age, gender, classroom and amount of time wearing the devices (see Table 4). The number of times a child initiated movement was negatively related to teacher ratings of attention, $\beta = -.54$, $p < .01$, and inhibitory control, $\beta = -.39$, $p < .05$, and to observer ratings of attention, $\beta = -.21$, $p = .26$, and inhibitory control, $\beta = -.46$, $p < .05$. The number of times a child initiated movement did not show significant associations with the measures of cognitive regulation, the HTKS, $\beta = -.18$, $p = .22$, and the DCCS, OR = .62, $p = .36$. Similarly, children's mean length of sedentary periods predicted teacher ratings of attention, $\beta = .47$, $p < .01$, and inhibitory control, $\beta = .33$, $p < .05$, and observer ratings of attention, $\beta = .26$, $p = .14$, and inhibitory control, $\beta = .42$, $p < .05$, but not measures the measures of cognitive regulation, that is, the HTKS, $\beta = .14$, $p = .26$, and the DCCS, OR = 1.36, $p = .52$. Finally, children's percentage of time in motion showed modest associations with teacher-rated attention, $\beta = -.29$, $p = .06$, and inhibitory control, $\beta = -.20$, $p = .25$, showed stronger associations with observer ratings of attention, $\beta = -.39$, $p < .05$, and inhibitory control, $\beta = -.52$, $p < .01$, but did not show associations with the measures of cognitive regulation, that is, the HTKS, $\beta = -.11$, $p = .48$, and the DCCS OR = 0.83, $p = .71$.

Correlations within and across Domains of Regulation

Overall, the results indicated associations between measures within domains of regulation (i.e., cognitive and behavioral) but not across domains of regulation. That is, the movement-based indicators and teacher and observer reports of behavioral regulation associated significantly with one another, but not with the measures of cognitive regulation. In addition to the significant pattern of associations among the accelerometer specifications with teacher and observer ratings reported above, the teacher and observer ratings also showed significant correlations with one another, rs = .36 to .64, $p < .05$ to $p < .001$, median $r = .51$, $p < .001$. Similarly, when comparing measures within the cognitive regulation domain, these showed significant associations with one another, as expected, $r = .56$, $p < .001$. The measures of cognitive regulation, however, showed only weak associations with behavioral regulation as assessed by teacher ratings, rs = .15 to .31, median $r = .20$, $p = .21$, and observer ratings, $rs = .06$ to .25, median $r = .18$, $p = .26$.

Discussion

Accelerometry appears to be a feasible way to assess children's behavioral regulation in the classroom. Our results confirm that it is possible to extract concrete behaviors from accelerometer data that show associations with teacher- and observer-ratings of children's behavioral regulation in the classroom. If validated in other studies and samples, accelerometry could fill the need for objective, precise measurement of children's behavioral regulation in real-world environments, a combination that other measures do not achieve.

Behavior ratings from teachers provide information about behavior in context but may be subjective; though observer ratings combine objective and contextual approaches, they are time and resource intensive and are likely a less precise measure than other ratings due to imperfect inter-rater reliability.

In contrast, accelerometers have ideal measurement properties. They are objective, measuring the same behaviors in the same way for all children, and are also precise, with standardized methods of converting physical motion into different states (i.e., moving vs. sedentary; Pate et al., 2006). This makes it possible for researchers to automate the observation and counting of discrete, concrete behaviors in the classroom. Because the accelerometer devices are small and lightweight, children can wear them as they complete regular classroom activities and they present a very low burden to participants. Because of these strengths, accelerometers can accomplish objective and precise measurement in children's everyday environments.

Using ambulatory sensors to assess children's behavior also extends and refines the amount of data that researchers can collect, allowing new research possibilities. Unlike human coders, sensors can observe children's behaviors for extended periods of time rather than codable "chunks" of behavior, which may not be representative of children's behavior more generally. The devices can also be used to record behavior in fine-grained detail as we have demonstrated in this study. This level of detail could be used to examine dynamic patterns of behavior in children's everyday environments. The current study conducted a preliminary examination of such patterns, employing confirmatory tests of hypothesized specifications of behavior. Given the amount of data available, however, exploratory, data-driven approaches could reveal many more patterns. Making use of this expanded and refined data collection will allow for new investigations, including examinations of within-person variability in behavior. Existing measures like lab-based assessments and adult reports of children's self-regulation are not designed to capture within-person variability, yet such variability is a key characteristic of human behavior and development (Nesselroade, 1991). Using this tool, future research could examine variability in children's behavior during different times of the day (e.g., morning vs. afternoon), during particular activities, and across study days.

In examining the validity of the accelerometer approach, we found evidence that children's behavioral regulation in the classroom is distinct from their cognitive regulation demonstrated in direct assessments. That is, all three of the classroom-based measures of children's behavioral regulation (i.e., teacher ratings, direct observations, and accelerometer specifications) showed significant correlations with one another, but only weak correlations with the measures of cognitive regulation used (i.e., DCCS, HTKS). Such a finding of low correlations observed between direct assessments of regulation and adult reports of conceptually similar skills is common (Toplak et al., 2013). Our findings suggest that the differences are not due to differences in objectivity in assessment. Findings from this study support a conceptual distinction between children's cognitive and behavioral regulation (McClelland et al., 2019).

Despite the potential of an accelerometer approach for assessing behavioral regulation in context, the approach does not appear to capture children's cognitive regulation. Actigraphy captures overt behavior, but cognitive regulation is highly internalized. As a result, cognitive regulation is likely still best assessed using structured tasks designed to challenge it rather than using a purely observational approach. Recent work has demonstrated it is possible to conduct structured assessments in environments that more closely mirror a classroom setting, namely by observing children's behaviors as they complete game-like tasks along with their peers (e.g., Ahmed et al., 2021; Howard et al., 2019). These semi-structured observational tools will remain important for assessing behaviors that cannot easily be captured using naturalistic, unstructured observations. Given its reliance on observable behaviors, the accelerometer approach will be most useful for assessing skills that manifest overtly in behavior and movement.

Limitations and Future Directions

Accelerometry appears to be a promising way to assess children's behavioral regulation, though it requires additional validation. The current study used a relatively small sample from five classrooms. Future work with a larger sample and more classrooms would enhance external validity. As for internal validity, additional concurrent and predictive validity measures, would help researchers to understand what the accelerometer approach captures and what it does not. Rather than using a subset of items from the Children's Behavior Questionnaire (Rothbart et al., 2001), future studies could examine a fuller set of adult ratings of children's behavior, measures of cognitive and emotional regulation, and children's pre-academic skills. Collecting these measures concurrently and longitudinally would help researchers to understand the degree of overlap of dimensions of regulation and whether dimensions matter differently for other domains of development. A larger sample would also allow factor analytic work in a structural equation modeling framework, an important future step for establishing validity.

Future work on the accelerometer approach could also examine whether technical decisions about sensor utilization could refine the measure. The placement of the sensors around children's waists and processing of the data in this study allowed us to distinguish between children's sedentary and non-sedentary behavior (Pate et al., 2006). This allowed us to convert raw accelerometry values to concrete, interpretable behaviors that have clear associations with teacher and observer reports of children's behavioral regulation in the classroom. However, it is possible that using this cutoff discards meaningful information. There may be other movements that do not rise to the level of the non-sedentary cutoff but could still be a marker of behavioral regulation. Furthermore, in the present study, children wore the accelerometer devices around their waists, a placement which captures full-body movement rather than movement of the arms or legs. This placement clearly allowed the accelerometers to capture meaningful behaviors, as indicated by associations with teacher and observer reports, but future work could test whether different placements of the sensor, such as on the wrist or ankle which would capture movement of the arms or legs, would provide additional meaningful information (Smith et al., 2020).

Though accelerometers are excellent tools for capturing motion, physical movement is only one indicator of behavioral regulation. Indeed, children's gaze and speech are other important indicators (Kofler et al., 2020; Rothbart et al., 2001), but these cannot be assessed using actigraphy. Other wearable sensors would be better suited to capturing such behaviors, for example head-mounted eye-tracking to capture gaze and visual attention (Slone et al., 2018; Yu et al., 2019) and microphones for speech (de Barbaro, 2019), and both have the potential for use in naturalistic settings. However, such devices are more conspicuous and may also be more intrusive for participants than a wearable accelerometer. If children's movement, gaze, and speech are all indicators of a latent factor (i.e., behavioral regulation), then it is possible that accelerometers would capture areas of covariance between these behaviors. The extent of such associations could be examined in future work.

Some future directions also emerge from aspects of our study design. Children's participation in this study took place over one day. Although the data collected were sufficient to establish associations among the measures of behavioral regulation, both the direct observations of behavior and accelerometers captured children's behavior at particular points in time while the teacher reports capture children's general behavior. It is possible that with observations and accelerometer data aggregated over several days, the association with teacher reports could be even stronger. It is also possible that the association could depend on the situations and contexts in which observational and accelerometer data are collected because expectations for children's behavior could shape the meaning of accelerometer-derived measures. Future work should examine this possibility.

Another consideration is that our study examined actigraphy during children's freeplay, a classroom activity in which children are expected to regulate their behavior according to classroom rules (e.g., to walk instead of run) but are free to move around the classroom and choose their activities. We found meaningful associations between teacher reports of behavioral regulation and movement-based indicators during this period, even though children were not instructed or expected to remain seated. It is possible that during other classroom activities which have behavioral expectations to restrict movement, such as snack time or when listening to a story, movement-based indicators of behavioral regulation could yield different information. Although our direct observations during circle time and accelerometer data during center-based freeplay appeared to capture similar information given their significant associations, it is not clear the extent to which they also capture different information given their only partial overlap. Future work should examine this question of whether assessing behavior during different activities could reveal similar or different information. Researchers could consider how children's behavioral regulation might vary according to teacher's behavioral expectations across activities. Doing so could reveal the sort of child-environment transactions thought to build children's regulation (Sameroff, 2010).

Conclusion

Assessing children's behavioral regulation in real-world settings is challenging, making valid and objective measurement approaches a boon to researchers. This feasibility study demonstrated the viability of an accelerometer-based approach to measure the ways that preschoolers' behavioral regulation manifests in children's physical movement in their classrooms. In validating the approach, we found evidence for correlations across measures within but not across domains of children's cognitive and behavioral regulation. These findings underscore that performance on direct assessments of cognitive regulation does not strongly predict behavioral regulation in the classroom. If validated in other samples and contexts, accelerometers and other measures of actigraphy could become important tools for studying children's behavioral regulation in their everyday settings, facilitating applied research and intervention.

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Data availability statement:

The data that support the findings of this study are not publicly available due to privacy or ethical restrictions. The data can be requested from the corresponding author.

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Research Highlights

- Discrete behaviors extracted from preschoolers' classroom-based, ambulatory accelerometer data showed significant associations with existing measures of behavioral regulation (i.e., teacher and observer reports).
- Assessments of cognitive regulation showed only modest associations with accelerometer-derived indicators and teacher and observer reports of behavioral regulation.
- If validated in other samples, the automated sensing of movement could be a promising tool to study children's behavioral regulation in real-world settings.

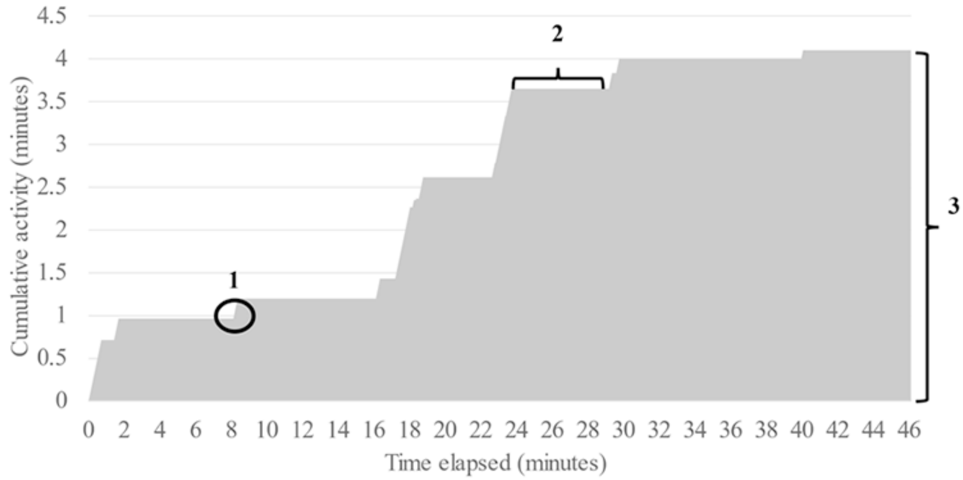

Figure 1.

Illustration of Behaviors Hypothesized to Index Behavioral Regulation in the Classroom for a 3-Year Old Participant: (1) Initiation of Movement, (2) Length of Sedentary Period; and (3) Total Time in Motion.

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Table 1

Alignment between Questionnaire Ratings of Behavioral Regulation and Accelerometer-Assessed Behaviors

Example item content from the CBQ and CBCL	Accelerometer-assessed behaviors
1. Moves from task to task without completing	1. Number of times child initiates movement
2. Has a hard time keeping mind on something, brief attention to tasks, trouble sustaining attention	2. Mean length of sedentary periods
3. Restless, can’t sit still, constantly in motion, overactivity	3. Percentage of time in motion

Note: CBQ = Child Behavior Questionnaire (Putnam & Rothbart, 2006), CBCL = Child Behavior Checklist (Achenbach, 1991).

Table 2

*Descriptive Statistics (*N *= 50)*

	***M*/ %**	***SD***	**Min.**	**Max.**
Participant characteristics				
Female	46%			
Age (years)	4.4	0.8	3.1	6
Race/ethnicity				
Non-Hispanic White	74%			
Hispanic White	14%			
Black, Asian, or Other race	12%			
Household income > 1.5x for metro area	63%			
Behavioral regulation measures				
Teacher ratings				
Attentional control (CBQ)	3.61	1.01	1.2	5
Inhibitory control (CBQ)	3.84	1.11	1	5
Observer Ratings				
Observed attention (RRSM)	3.36	0.66	1.5	4
Observed inhibitory control (RRSM)	3.49	0.66	1.25	4
Accelerometer-based measures				
Number of times child initiated movement	25.9	14.6	1	59
Mean length of sedentary periods (in seconds)	127	96	20	402
Percentage of time in motion	21.1%	13.7%	4.7%	57.2%
Cognitive regulation measures				
Inhibitory control (HTKS)	26.85	23.16	0	60
Attention shifting (DCCS)	74%			

Note: CBQ = Children's Behavior Questionnaire (Putnam & Rothbart, 2006); RRSM = Regulation-Related Skills Measure (McCoy et al., 2017); HTKS = Head-Toes-Knees-Shoulders (Ponitz et al., 2009); DCCS = Dimensional Change Card Sort (Zelazo, 2006).

Table 3

Correlation Matrix

	1	2	3	4	5	6	7	8	9	10
1. Teacher-rated attention (CBQ)										
2. Teacher-rated inhibitory control (CBQ)	.85***									
3. Observed attention (RRSM)	.36*	.52***								
4. Observed inhibitory control (RRSM)	.50***	.64***	.84***							
5. HTKS	.15	.15	.15	.25						
6. DCCS (post-switch trial)	.24	.31*	.06	.20	.56***					
7. Number of times child initiated movement	−.55***	−.43**	−.17	−.43**	−.07	−.15				
8. Mean length of sedentary periods (natural log)	.47***	.38**	.25	.43**	−.02	.16	−.85***			
9. Percentage of time in motion	−.29*	−.31*	−.43**	−.49***	.01	−.17	.64***	−.84***		
10. Female	.46***	.43**	.25	.43**	.08	.29*	−.32*	.18	−.14	
11. Age (years)	−.18	−.10	.02	−.02	.66***	.30*	.22	−.25	.20	.02

* $p < .05$

** $p < .01$

*** $p < .001$.

Note: CBQ = Children’s Behavior Questionnaire (Putnam & Rothbart, 2006); RRSM = Regulation-Related Skills Measure (McCoy et al., 2017); HTKS = Head-Toes-Knees-Shoulders (Ponitz et al., 2009); DCCS = Dimensional Change Card Sort (Zelazo, 2006).

Table 4

Regression Models Predicting Teacher Ratings, Observer Ratings, and Lab-Based Assessments of Self-Regulation

	Number of Times Child Initiates Movement				Mean Length of Sedentary Periods (Natural Log)				Percentage of Time in Motion			
	Est.	**S.E.**	***p***	**β/OR**	**Est.**	**S.E.**	***p***	**β/OR**	**Est.**	**S.E.**	***p***	**β/OR**
Behavioral regulation												
Attentional control (teacher-rated)	−0.04	0.01	.001	−0.54	0.67	0.18	.001	0.47	−2.15	1.11	.059	0.29
Inhibitory control (teacher-rated)	−0.03	0.01	.011	−0.39	0.51	0.21	.018	0.33	−1.64	1.4	.248	−0.2
Attentional control (observed)	−0.01	0.01	.257	−0.21	0.25	0.16	.137	0.26	−1.86	0.85	.037	−0.39
Inhibitory control (observed)	−0.02	0.01	.013	−0.46	0.4	0.15	.016	0.42	−2.47	0.87	.008	−0.52
Cognitive regulation												
HTKS	−0.28	0.22	.215	−0.18	4.48	3.92	.26	0.14	−17.89	24.89	.476	−0.11
DCCS	−0.03	0.04	.356	0.62	0.44	0.67	.519	1.36	−1.35	3.58	.707	0.83

Note: CBQ = Children's Behavior Questionnaire (Putnam & Rothbart, 2006); RRSM = Regulation-Related Skills Measure (McCoy et al., 2017); HTKS = Head-Toes-Knees-Shoulders (Ponitz et al., 2009); DCCS = Dimensional Change Card Sort (Zelazo, 2006). All models used OLS regression models except for the model predicting attention shifting (DCCS), which used logistic regression.