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ORIGINAL PAPER

Mindful Movement Intervention Applied to at Risk Urban School Children for Improving Motor, Cognitive, and Emotional-Behavioral Regulation

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Abstract

Objectives Preliminary evidence has supported the notion that mindful movement-based practices may offer benefits for self-regulation, particularly for vulnerable children. However, this evidence has principally stemmed from subjective assessments of behavioral change, leaving the underlying mechanisms undetermined. The present study aimed to investigate the efficacy of an in-school mindful movement intervention (MMI) for at-risk children within an urban public school for enhancing motor, cognitive, and emotional-behavioral regulation, including control of disruptive and inattentive behaviors characteristic of ADHD.

Method Participants included 38 (age 7–8 years) children who received twice weekly, in-school MMI, including a modified Tai Chi sequence, yoga and biomechanical warm-ups, imaginative play, and reflection. Parent and teacher ratings of disruptive behaviors, and objective measures of motor and cognitive control, were collected at baseline and after 5 months of MMI.

Results Significant improvements in teacher ratings of inattentive, hyperactive/impulsive, oppositional, and other disruptive behaviors were observed. Significant improvements were also observed for objective measures of both cognitive control and motor control with particular reductions in both right and left dysrhythmia.

Conclusions MMI was associated with improvements across objective and subjective assessments of motor, cognitive, and behavioral control. This proof-of-principle investigation provides preliminary support for the efficacy and feasibility of a novel MMI implemented as part of the school day in an urban school setting with 7–8-year-old children to augment development of at-risk youth.

Keywords Mindful movement intervention · Urban public school · Behavioral control · Tai Chi · Yoga · Imaginative play

Mindfulness is defined as intentionally directing attention to present-moment experiences with an attitude of curiosity, openness, and acceptance (Bishop et al., 2004). Originating from Buddhist practices which utilized meditation techniques to minimize personal suffering, mindfulness approaches have since been adopted within the context of contemporary psychology to both increase awareness and skillfully respond to mental processes that contribute to emotional distress and maladaptive behavior. Clinical applications of mindfulness now include mindfulness-based stress reduction (Kabat-Zinn, 1982), which is employed for managing chronic pain and illness as well as a broad range of emotional and behavioral disorders. Moreover, mindfulness practices have been shown to improve control over emotion, attention, and behavior, particularly for populations with impaired self-regulation such as in generalized anxiety disorder, substance

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abuse, eating disorders, post-traumatic stress disorder, and at-risk youth (Dunning et al., 2019).

Within impoverished urban environments, such as Baltimore City, USA, children are at increased risk for developing emotional or behavioral problems as a result of exposure to adverse childhood experiences (ACEs)—such as experiencing/witnessing violence, abuse/neglect, exposure to substance abuse, mental health problems, or instability due to parental separation or incarceration. Tragically, 30% of children in Baltimore City have experienced more than two incidences of ACE during critical windows of development. This striking health inequity is compounded by high rates of child poverty (33.3% in Baltimore City), such that Baltimore City children are at substantial risk for emotional and behavioral health difficulties, yet are less likely to receive needed treatment (Jefferson, 2019). Regarding children exposed to trauma or ACEs, mindfulness may provide an indirect effect on negating the acute response to trauma and stress, as well as inhibit underlying consequences of chronic exposure to stress and trauma, including psychiatric, metabolic, and cardiovascular disease (Ortiz & Sibinga, 2017; Wall, 2005).

Introducing mindfulness during childhood, a developmental window characterized by rapid neurodevelopment, may enhance core cognitive skills to support academic and social functioning via supporting self-regulation and cognitive control — an individual's capacity to regulate, control, and manage other cognitive processes such as planning, working memory, attention, and response inhibition (Kuramoto, 2006; Weare, 2013). Associations between mindfulness and improved cognition and attention have been identified within the context of both typical and atypical development (Clark et al., 2015, 2020), suggesting that mindfulness-based intervention strategies could offer improvements for a diverse range of developmental trajectories.

Importantly, among children, mindfulness-based interventions are effective in group settings and have been successfully integrated into the school day (Dariotis et al., 2017; Krebs et al., 2022; Maynard et al., 2017; Mendelson et al., 2010; Zenner et al., 2014). Given that children spend the majority of time in the school environment and that child mental health problems are associated with reduced academic achievement, increased detentions/suspensions/expulsions, and high school dropout, schools are a natural setting in which to support children's emotional and behavioral health. Further, school-based mental health services often increase family comfort with seeking help by reducing a number of barriers to mental health care including reducing logistical challenges (e.g., transportation, scheduling, ability to pay) and stigma for seeking services (Lindsey, 2017). Unfortunately, few schools have the resources required to respond to large numbers of students with a wide range of psychosocial difficulties that interfere with their learning and performance (Adelman & Taylor, 2006). Research has shown that school-based mental health services strongly benefit from schools partnering with mental health organizations. A mindfulness-based intervention offered within school settings therefore offers strong promise as a highly scalable and sustainable approach for successful outreach to a wide range of children.

There is increasing scientific evidence supporting mindful movement interventions (MMIs) for addressing mental health challenges, including emotional trauma, anxiety/mood difficulties, and symptoms of attention-deficit/hyperactivity disorder (ADHD) and related executive dysfunction (Cairncross & Miller, 2020; Clark et al., 2020; Dunning et al., 2019; Ortiz & Sibinga, 2017). Mindful movement skills can be augmented through training and can provide sustainable, life-long tools for individuals that suffer from these difficult to treat conditions as well as individuals without mental health problems. A range of age- and group-specific MMIs have been developed to enhance mindfulness skills and have been applied to both children and adolescents (Dunning et al., 2019; Huguet et al., 2019). MMIs are relatively cost-effective and can be implemented and taught in a number of settings, including public schools. This provides access to skills and resources for promoting positive developmental trajectories by improving self-regulation, particularly within disadvantaged, trauma-exposed, at-risk youth in the urban public school setting and other low-resource school environments.

Mindful movement interventions may incorporate a range of exercises including yoga, breathing, and moving meditations such as Tai Chi. Tai Chi is a Chinese mind–body exercise that incorporates a wide range of mindful movements, including slow, meditative, flowing, dance-like motions often connected to imagery. Most importantly, it incorporates the purposeful regulation of movement and coordination between the breath, mind, and body. Practicing Tai Chi is unique in that it can be practiced without special equipment or facilities, performed individually or in groups, and is well suited for participants of all ages. Studies have shown that Tai Chi is associated with a number of health benefits such as increased strength, flexibility, balance, mobility, and posture, as well as reduced fears of falling in elderly, reduced stress, and increased cognitive functioning (Hackney & Earhart, 2008; Kuramoto, 2006). Given these benefits, introducing Tai Chi as a component of MMI for children and adolescents may prove to be an effective method for enhancing development of motor, cognitive, and attentional control.

Preliminary evidence supports the notion that MMI incorporating Tai Chi may improve symptoms of inattention, hyperactivity, and anxiety in adolescents with ADHD, in addition to improved conduct, with persistent improvement two weeks after the intervention (Hernandez-Reif et al., 2001). This evidence supports the notion that Tai Chi may improve self-regulation of attention, behavior, and emotions, thereby having beneficial effects as a supplemental therapy for adolescents with ADHD. In addition, efficacy of MMI for school age children has been demonstrated, with findings revealing improved parent ratings of inattention, hyperactivity/impulsivity, oppositionality, emotional lability, and executive dysfunction (Clark et al., 2020). Objective assessment further revealed that children showed improved motor control, with these motor improvements correlated with reduced ADHD symptoms. This provides initial evidence that objective measures of motor control may be predictive of improvements in behavioral control across a range of behavioral phenotypes and thereby could serve as an objective biomarker for MMI (Bernard & Mittal, 2015; Clark et al., 2020). Furthermore, this evidence suggests that MMI may be implemented in school settings to target under-served populations such as at-risk youth in low-resource school environments.

The present study evaluated the efficacy and feasibility of an existing school-based multimodal MMI program incorporating elements of Tai Chi, yoga, and imaginative play, delivered in a group format to second and third grade students in an urban public school setting (Baltimore City public school). The multimodal MMI format employed a range of mindful movement approaches to better engage children throughout the MMI and offer diverse modalities through which to learn self-regulation via mindful movement. Outcomes of the MMI were examined with subjective measures (i.e., parent and teacher ratings) of ADHD traits and disruptive behavior as well as objective measures of motor and cognitive control administered pre- and post-intervention. We hypothesized that after MMI, children would show improvements in ADHD traits and disruptive behavior, as well as objective measures of motor and cognitive control.

Method

Participants

The study was conducted with second and third grade students at City Neighbors Charter School, a public school located in Baltimore, MD. The MMI program was developed and implemented through a close collaborative partnership between the City Neighbors school (Kate Seidl, Principal) and the Center for Neurodevelopmental and Imaging Research (CNIR) at Kennedy Krieger Institute (Stewart Mostofsky, Director). All students participated in the MMI program ($n=58$), with a subset of students and their parents ($n=38$) consenting/assenting to participate in the study. Children were not excluded on the basis of any prior mental health or medical diagnoses. Students and their parents who chose to participate in the study provided oral assent and written informed consent. The study was conducted according to both Johns Hopkins University Institutional Review Board and Baltimore City Public School Institutional Review Board guidelines.

Analyses were conducted on 38 participants (28 girls) with a mean (*SD*) age of 8.40 (0.58) years and socio-economic status (SES) score of 41.50 (17.95). The self-reported race of the sample was 55% Caucasian and 45% non-Caucasian. One participant did not complete the study because they were unable to understand instructions related to overall intellectual/language ability, leaving a maximum sample size of 37 for analyses. Several participants did not complete all instruments, so each measurement was analyzed separately using only participants with data from both time points.

Procedure

The MMI program involved a holistic approach to mindful movement, including enrichment activities in an urban school setting. The program was conducted separately for second and third grade classes, including two 45-min sessions per week that took place in the school gymnasium during the regular school day, on Tuesday and Thursday mornings. Students were led by instructors in a modified Tai Chi sequence, yoga and biomechanical warm-ups, breathing, imaginative play, and reflection. The Tai Chi sequence incorporated several styles of Tai Chi including Yang (large, sweeping, slow, and graceful movements), Wu (postural control and balance), and Sun (fluid movement resembling a choreographed dance). The yoga exercises included elements of Hatha yoga (static poses combined with mindful breathing and meditation) and Vinyasa yoga (breath-synchronized flow between postures, e.g., Sun Salutations). This variety of mind–body exercises provided sufficient novelty to keep children engaged while providing multiple contexts in which to learn self-regulation through controlled movement and coordination between the breath, mind, and body. Three instructors worked together over the course of the year and were trained to consistently administer the intervention and rate student outcomes. Furthermore, a Fidelity Checklist was used to ensure that all instructors were equivalently covering the core activities involved in MMI. A detailed protocol for the MMI is included in Supplementary Information**.**

Within four weeks of the beginning of the intervention, in September 2019, questionnaire measures of disruptive behavior, ADHD symptoms, and irritability (separately rated by teachers and parents) were collected, and research assistants administered performance-based objective assessments individually to each child outside of their classroom during their typical school day. These same measures were assessed again after 5 months of MMI, in February of 2020. The original study design included a third measurement time point at the end of the school year; however, due to the SARS-COVID-19 pandemic, the intervention was forced to conclude prematurely, and data were not obtained from the final time point. As such, results are reported for the first and second time points.

Measures

Medical and Developmental History Form (Parents Only) This form was completed by parents at baseline providing demographic information (e.g., age, sex, race, maternal education) and was used to calculate the Hollingshead SES scores (Hollingshead, 1975).

Strengths and Weaknesses of ADHD-Symptoms and Normal-Behavior (SWAN) The SWAN is an assessment based upon observations of normal and abnormal distributions of attention scales in samples from diverse populations and shows high reliability and validity (Brites et al., 2015; Swanson et al., 2001). This 30-item rating scale measured symptoms of ADHD, as well as oppositional defiant disorder (ODD). Parent and teacher raters evaluated the child at baseline and post-intervention by comparing them to other children within their age group on skills related to focusing attention, controlling activity, and inhibiting impulses. Each item was scored by the rater from − 3 to + 3 (far below average, i.e., weaknesses, to far above average, i.e., strengths) and scores were averaged (range − 3 to + 3) across items within a scale (Inattentive, Hyperactive-Impulsive, ADHD Combined, Oppositional Defiant Disorder, Sluggish Cognitive Tempo).

Multidimensional Assessment of Preschool Disruptive Behavior (MAP-DB) The MAP-DB, an assessment with high psychometric internal validity that was developed by a team of experts in early childhood, clinical assessment and treatment, and developmental epidemiology, was used to measure disruptive behaviors with four subscales: temper loss, aggression, non-compliance, and low concern for others (Wakschlag et al., 2014, 2018). Teachers and/or parents completed the Early School Age version of the 77-item questionnaire, which is designed for children between the ages of 6–8 years old. Ratings were given on a 6-point scale from 0 to 5 (0 = *never*; 1 = *rarely*; 2 = *some*; 3 = *most*; 4 = *every day of the week*; 5 = *many times each day*) and were summed to generate a total score for each scale (Temper Loss, Aggression, Noncompliance, Low Concern for Others, and Total Disruptive Behaviors as the sum of all four subscales).

The Physical and Neurological Examination for Subtle Signs (PANESS) The PANESS is a structured, norm-referenced neuromotor examination with good test–retest reliability and validity within an age range of 5 to 17 years (Denckla, 1985; Vitiello et al., 1989). Tasks included untimed assessment of gaits and stations and timed assessment of rapid/sequential movements of the feet, hands, and tongue. Total score and individual scores from examination of gaits, stations, and timed motor coordination tasks were analyzed. Higher scores indicate worse performance.

Lateral Gaze Assessment The lateral gaze assessment is a measure of motor persistence (Kertesz et al., 1985), whereby participants were asked to sustain lateral gaze for 20 s, which was timed with a stopwatch. Examiners were trained by a behavioral neurologist (SHM) and achieved an interrater reliability of 0.90 or greater on practice examinations prior to testing. The examiner held a pencil approximately 45° from the plane between the examiner and patient midlines in the patient's right visual field. The trial terminated at 20 s or earlier if the child's eyes deviated from the indicated fixation point. This procedure was conducted for the right visual field, then the left visual field, and then repeated for both visual fields. A perfect score (80 s) indicated no errors in holding the gaze for 20 s twice on the right and twice on the left. The dependent measure was the sum of left and right lateral gaze scores, with two trials on the right side and two trials on the left side for a total of four trials of 20 s each. Two trials were collected, each with right and left gaze direction. Measures analyzed included the sum of both trials for each gaze direction, as well as the total sum of right and left gaze over both trials.

Developmental Neuropsychological Assessment (NEPSY) Statue Task The NEPSY Statue Task is a measure of motor persistence in which the child was asked to maintain a fixed body position with eyes closed during a 75-s period (Korkman et al., 1998). Examiners were trained by a behavioral neurologist (SHM) and achieved an interrater reliability of 0.90 or greater on practice examinations prior to testing. Observations were made every 5 s for the presence of body movement, eye opening, and talking. During the task, the examiner made a series of distracting noises (e.g., dropping a pencil, coughing). A score of 2 was recorded for each 5-s interval in which there was no movement, eye-opening, or talking, and a score of 1 was recorded for each interval in which there was one type of error. A score of 0 was recorded if there were two or more errors during a 5-s epoch. The total scores ranged from 0 to 30, with higher scores indicating less motor persistence and inhibitory control. Total raw score was used as the dependent variable for this task.

Delis-Kaplan Executive Function System (D-KEFS) Trail Making Test The D-KEFS is a highly reliable battery of standardized tests designed to evaluate one's ability to employ cognitive control, and it has been normed and validated for ages 8 years through adulthood (Erdodi et al., 2018). The Trail Making Test (TMT) consists of five conditions assessing speed and accuracy of visual search, number sequencing, letter sequencing, and number-letter switching. Raw scores (completion time in ms) for each task condition were analyzed, in addition to a contrast between the task condition with the greatest cognitive demand vs the standard task condition (number-letter switching — visual search).

Go/No-Go (GNG) Task The GNG task, which shows good construct validity, requires participants to exercise cognitive control while inhibiting responses to cues (Votruba & Langenecker, 2013). Participants were seated in front of a computer on which individual red or green spaceships were presented. They were instructed to push a button with their right index finger as quickly as possible in response to green spaceships only. Use of familiar color elements (green for "go"; red for "no-go") minimized the working memory load and other cognitive demands of this test. Cues appeared on the screen for 300 ms and were presented once every 1800 ms (1500 ms interstimulus interval). Cues were weighted toward green spaceships at a ratio of 3:1 (173 go cues; 44 no-go cues), intensifying the need to inhibit a rapid, habitual motor response. The total time of the task was 8 min 19 s. The primary dependent variables were commission error rate (ComRate), defined as incorrectly pressing for a red spaceship, and tau, an ex-Gaussian parameter quantifying the skewed tail of the RT distribution due to slow, infrequent responses. Tau was examined as an index of response variability separate from response speed rather than standard deviation (*SD*) of RT, which is highly correlated with mean RT. We also examined mu and sigma as indicators of response speed and variability in the "normal" part of the RT distribution, as well as traditional mean and SD of RT measures. Ex-Gaussian indicators were computed in Matlab version 2019b (The Mathworks, Inc., Natick, MA) using the DISTRIB toolbox (Lacouture & Cousineau, 2008). Responses faster than 200 ms were excluded from all RT analyses, and all participants had a fast go rate (i.e., proportion of go trials with RTs $<$ 200 ms) below 0.30, omission error rate below 0.50, and an acceptable ex-Gaussian fit index ($n < 2000$).

Feasibility The feasibility of the MMI was assessed on four dimensions: Acceptability, Implementation, Practicality, and Integration (Bowen et al., 2009). *Acceptability* was assessed using a combination of objective assessments for students and subjective assessments for parents regarding reactions to the intervention. *Implementation* was defined as the extent to which the program was delivered as planned and proposed. *Practicality* was evaluated based upon the delivery of the MMI within the constraints of limited resources such as time and space. *Integration* was determined by the degree of system changes within the school infrastructure required to implement the MMI.

Data Analyses

Participants with missing time points data were removed prior to analysis of each separate outcome measure. Raw data distributions for each measure were visualized and analyzed in RStudio (R version 3.6.1), and non-uniform distributions were normalized using the most effective transformation prior to statistical analysis. Transformed outcome (dependent) measures were tested for within-subjects pre- to post-intervention differences using multivariate mixed effects regression. The *lme4* package was used for linear mixed effects modeling, including the random effect of participant and fixed effect of time point. Effect sizes were calculated according to Eq. 1 (Brysbaert & Stevens, 2018).

$$d = \frac{difference\ between\ the\ means}{\sqrt{variance\ intercept_{participant} + variance_{residual}}} \quad (1)$$

Results

Subjective Assessments of Behavioral Control

On the SWAN rating scale ($n=29$), teacher ratings indicated a significant improvement from pre- to post-intervention across all SWAN subscales (Table 1), including Inattentive ($p<0.001$, $d=0.33$), Hyperactive-Impulsive ($p<0.001$, $d=0.58$), ADHD-Combined ($p<0.001$, $d=0.48$), Oppositional Defiant Disorder (ODD) ($p=0.008$, $d=0.43$), and Sluggish Cognitive Tempo (SCT) ($p<0.001$, $d=0.55$). A similar set of findings was observed with the parent variation of the assessment across all subscales. However, the sample size and effect sizes were smaller ($n=22$), and only ODD was significant ($p=0.041$, $d=0.28$) (see Table 1).

Similarly to the SWAN, teacher ratings on the MAP-DB ($n=29$) suggested improvements in disruptive behavior across all subscales, with significant improvements in Temper Loss ($p=0.013$, $d=0.59$) and Disruptive Behaviors ($p=0.030$, $d=0.46$) (see Table 1). It is important to note that these measures were highly skewed due to the nature of the assessment as intended for clinical samples and therefore referring to the degree of problematic behavior or symptoms. Like the SWAN, the same trends were observed for the parent variation of the assessment, though results were relatively under-powered ($n=21$; Table 1).

Objective Assessments of Motor Control

For the PANESS ($n=36$; Table 2), significant reductions were observed in bilateral dysrhythmia scores ($p=0.005$,

Table 1 Summary of subjective assessments at baseline and post-intervention

Measure		Rater	n	Baseline	n	Post-MMI	p (d)
SWAN	Inattention	P	22	−0.16 (1.05)	22	−0.32 (1.05)	0.204 (0.15)
		T	29	0.25 (1.09)	29	−0.10 (1.08)	<0.001 (0.33)*
	Hyperactive/Impulsive	P	22	−0.41 (1.16)	22	−0.57 (1.02)	0.278 (0.14)
		T	29	0.088 (0.91)	29	−0.44 (0.90)	<0.001 (0.58)*
	ADHD Combined	P	22	−0.28 (1.05)	22	−0.44 (0.90)	0.152 (0.16)
		T	29	0.19 (0.98)	29	−0.27 (0.92)	<0.001 (0.48)*
	ODD	P	22	−0.43 (0.93)	22	−0.69 (0.97)	0.041 (0.28)*
		T	29	−0.17 (0.77)	29	−0.54 (0.97)	0.008 (0.42)*
	SCT	P	22	−0.48 (0.97)	22	−0.50 (1.07)	0.937 (0.01)
		T	29	0.25 (1.06)	29	−0.33 (1.08)	<0.001 (0.55)*
MAP – DB	Temper Loss	P	21	21.33 (17.98)	21	18.48 (16.10)	0.180 (0.20)
		T	29	5.07 (8.77)	29	2.17 (5.12)	0.013 (0.59)*
	Aggression	P	21	17.24 (19.36)	21	14.86 (14.65)	0.361 (0.13)
		T	29	3.69 (6.89)	29	1.83 (3.97)	0.221 (0.27)
	Non-compliance	P	21	29.67 (22.39)	21	24.76 (20.10)	0.093 (0.22)
		T	29	6.00 (8.60)	29	3.55 (7.11)	0.061 (0.37)
	Low Concern for Others	P	21	13.52 (11.09)	21	11.38 (9.21)	0.251 (0.22)
		T	29	1.59 (2.31)	29	0.93 (2.45)	0.066 (0.44)
	Disruptive Behavior	P	21	81.76 (67.33)	21	69.48 (54.97)	0.201 (0.17)
		T	29	16.34 (24.52)	29	8.48 (16.61)	0.030 (0.46)*

All measures are presented as mean (standard deviation) for the parent (P) and teacher (T) assessments, with p-values (effect sizes). MAP-DB: Means were calculated from the sum of item ratings, ranging from 0 to 5 (no disruptive behaviors–many disruptive behaviors per day). SWAN: Means reflect raw scores, ranging from −3 to 3 (far above average to far below average). *$p<0.05$

$d=0.53$). There were no significant differences in Total Gaits scores ($p=0.207$, $d=0.27$), Total Timed scores ($p=0.449$, $d=0.11$), or bilateral Total Overflow scores ($p=0.765$, $d=0.04$). There were no significant changes in motor persistence on either the lateral gaze task ($n=35$; Table 2) or NEPSY statue ($n=37$; Table 2), as measured by lateral gaze fixation (sum of left and right, $p=0.837$, $d=0.03$), and the sum of Statue scores ($p=0.473$, $d=0.12$).

Objective Assessments of Cognitive Control

There were significant improvements in performance on the D-KEFS Trail Making Test ($n=20$; Table 2), selectively in the task condition with the greatest demands on cognitive flexibility/task-switching and working memory, as demonstrated by faster speed during the Number Letter Sequencing (NLS) condition ($p=0.016$, $d=0.60$). In contrast, there were no significant effects during task conditions with fewer demands, including Visual Search (VS) speed ($p=0.430$, $d=0.25$) and Number Sequencing (NS) speed ($p=0.344$, $d=0.28$). Furthermore, when contrasting the faster speed during NLS (with greater demands) relative to the VS (lower demands) by way of a difference score (NLS-VS) calculated for pre- and post-intervention, there was a stronger effect for improved performance on the NLS-VS difference score ($p=0.009$, $d=0.67$), suggesting specificity of improvement in cognitive control.

There was also evidence of improved cognitive control as assessed by performance on the GNG Task ($n=37$; Table 2). Specifically, there was a significant reduction in mean response time (Mean RT) from pre- to post-intervention ($p=0.024$, $d=0.28$). Although a similar pattern of improvement was observed across GNG measures, results were weaker for commission error rates ($p=0.069$, $d=0.26$), standard deviation of RT (SD RT) ($p=0.358$, $d=0.12$), tau ($p=0.310$, $d=0.13$), mu ($p=0.219$, $d=0.15$), and sigma ($p=0.197$, $d=0.21$). These results suggest some improvement in GNG task performance, primarily with regard to response speed and inhibitory control.

Feasibility

The *Acceptability* of the MMI was high, given the positive responses to objective and subjective assessments, and the *Implementation* was effective, provided that the mindful movement classes were consistently delivered throughout the school year by the teachers in accordance to the Instruction Manual (provided in Supplementary Information). *Practicality* was determined as reasonable given the successful

Table 2 Summary of objective assessments at baseline and post-intervention

Measure		*n*	Baseline	*n*	Post-MMI	*p* (*d*)
PANESS	Dysrhythmia	36	6.56 (2.59)	36	5.22 (2.49)	0.005 (0.53)*
	Total Gaits	36	5.00 (1.71)	36	4.58 (1.59)	0.207 (0.27)
	Total Timed	36	12.69 (4.93)	36	12.19 (5.20)	0.449 (0.11)
	Total Overflow	36	9.33 (4.10)	36	9.25 (4.56)	0.765 (0.04)
Motor Persistence	Lateral Gaze	35	80.63 (33.92)	35	79.66 (32.90)	0.837 (0.03)
	NEPSY Statue	37	24.00 (5.20)	37	24.41 (5.40)	0.473 (0.12)
D-KEFS	NLS	20	196.35 (45.95)	20	165.15 (56.67)	0.016 (0.60)*
	VS	20	38.40 (17.53)	20	40.90 (13.46)	0.430 (0.25)
	NS	20	60.55 (15.35)	20	57.85 (21.20)	0.344 (0.28)
	LS	20	85.25 (30.48)	20	73.10 (24.24)	0.086 (0.44)
	NLS-VS	20	157.95 (44.84)	20	124.25 (54.85)	0.009 (0.67)*
GNG	Mean RT	37	448.95 (91.43)	37	423.38 (84.50)	0.024 (0.28)*
	Commission Error	37	0.48 (0.18)	37	0.43 (0.18)	0.069 (0.26)
	SD RT	37	205.67 (126.40)	37	180.69 (88.89)	0.358 (0.12)
	Tau	37	166.52 (91.48)	37	147.88 (66.12)	0.310 (0.13)
	Mu	37	282.43 (46.21)	37	275.48 (45.24)	0.219 (0.15)
	Sigma	37	31.65 (17.46)	37	28.15 (15.41)	0.197 (0.21)

All measures are presented as mean (standard deviation), with *p*-values (effect sizes). *$p < 0.05$. PANESS means reflect scores, whereby higher scores indicate worse performance. Lateral Gaze means reflect total sum of right and left gaze scores, whereby higher scores indicate better performance. NEPSY Statue means reflect total scores, whereby higher scores indicate better performance. D-KEFS means reflect raw scores, whereby higher scores indicate worse performance. GNG Mean RT reflects mean response times, whereby longer response times indicate better performance; Commission Error rates reflect incorrect responses, whereby greater scores indicate worse performance; SD RT reflects the standard deviation of response times, whereby greater values indicate worse performance; Tau reflects response variability, whereby greater values indicate worse performance; Mu and Sigma reflect response speed and variability, whereby greater values indicate worse performance

delivery of the MMI within the limited constraints of the school setting, including limited time (90 min total per week) and space (multipurpose room/gymnasium). *Integration* of the MMI program was successful, given that teachers were able to work with their schedules so that students were able to commit time to the program without detracting from their regular weekly activities.

Discussion

The objective for the current study was to evaluate the feasibility and preliminary evidence for efficacy of a novel multimodal MMI that was incorporated into the school-day curriculum within an urban public-school setting. Our decision to include multiple mindful movement modalities (Tai Chi, yoga, breathing, and imaginative play) provided consistent engagement of students throughout the classes as well as diverse formats for students to learn self-regulation through mindful movement. Our findings, comparing pre- to post-MMI evaluations, reveal improvements associated with this intervention across subjective and objective measures of behavioral, motor control, and cognitive control, including ADHD-relevant dimensional traits.

For subjective parent and teacher ratings of behavior, all SWAN subscales showed highly significant improvements across time points. These findings were true for both teacher and parent ratings, although effect sizes were relatively smaller for parents compared to teachers, potentially due to smaller sample sizes and possibly bias and lack of blinding and/or differences in child behaviors between the school and home environments. Similarly, all of the parent and teacher MAP-DB subscales trended toward improvement, although not all effects were significant. This could be in part due to the skewed distributions, likely caused by the assessment's bias toward children with an ADHD diagnosis. The MAP-DB is designed to quantify clinical impairment in regulation of disruptive behavior and is therefore skewed toward the elevated range. Given that our sample was obtained from a diverse non-clinical population, the MAP-DB may not be the most appropriate measure for assessing disruptive behavior problems in our sample. This is in contrast to the normally distributed SWAN, which proved better able to assess for changes in ADHD-associated disruptive behaviors for the broader community population included in this study.

The broad range of improvements in ADHD symptoms and other disruptive behavior observed for this study is consistent with findings from recently published investigations on the efficacy of MMI for children with ADHD, wherein improvements observed (using the SWAN and a different rating scale, the Conners-3 Parent Rating Scale (Conners et al., 2011)) included ADHD symptom domains (inattention and hyperactivity/impulsivity), oppositional defiant disorder, emotional lability, and clinical global impression (Clarke et al., 2020; Poissant et al., 2019; Siebelink et al., 2022). Taken together with our study in the non-clinical context, these similar patterns of improvement suggest that MMI incorporating Tai Chi may provide substantial benefits for a wide range of children, including those with ADHD as well as general populations of children, including those in urban school settings.

Findings of parent and teacher ratings showing improved behavior, while subjective and with potential bias, are nevertheless supported by findings of improved performance on objective measures of cognitive control. Notably, children showed improved performance on the DKEFS trails task, in particular for the condition designed to assess cognitive control (number letter sequencing), for which there is increased demand for working memory and cognitive flexibility, consistent with previous findings (Anusuya et al., 2021). In contrast, significant change was not seen for the task conditions with lesser cognitive demands (visual scanning and letter sequencing). These findings are consistent with published studies with a range of populations (children and adults) revealing beneficial effects on cognitive control and associated executive functions, including short- and long-term memory and working memory (Möller & Aschersleben, 2020; Quach et al., 2016; Yu et al., 2021). Our results and prior findings appear to lend support for proposed frameworks in which MMI enhances cognitive and behavioral control through skilled practice of actions requiring efficient and effective allocation of attention (Clark et al., 2015).

Assessments of developmental motor function, using the PANESS, revealed that children showed particular improvements after intervention with dysrhythmia (both right and left sided). Combined with previous literature, our results suggest that MMI contributes to parallel improvements in motor (PANESS) and cognitive control (SWAN SCT, GNG, DKEFS), suggesting that these measures might serve as readily measurable, objective biomarkers for assessing response to MMI across diverse pediatric populations (Clark et al., 2020). Motor and cognitive functions are indicators of brain development throughout childhood, particularly within the context of the frontal lobe and cerebellum. The frontal lobe plays an integral role in acquiring and executing both motor and cognitive control functions, while the cerebellum plays a modulatory role throughout neurodevelopment and optimizes learning for a wide range of motor and cognitive skills (Rosch & Mostofsky, 2019; Stoodley, 2016). Furthermore, in neurodevelopmental conditions where motor and cognitive control are impacted, such as ADHD and autism, the frontal lobe and cerebellum (and neural circuits that involve these regions) show alterations that are consistent with behavioral aberrations (Rosch & Mostofsky, 2019; Stoodley, 2016). Perhaps MMI alters these neural substrates of motor and cognitive control, which ultimately result in the observed behavioral improvements. Indeed, neural observations following mindfulness training include increased cortical thickness in the frontal pole, altered thalamo-cortical and cortico-subcortical-cerebellar connectivity, and strengthened cognitive network activity correlated with improvements in mindfulness and behavioral regulation (Chen et al., 2021; Ng et al., 2021; Santarnecchi et al., 2021; Yu et al., 2021).

The present investigation provides evidence supporting the efficacy and feasibility of a novel multimodal MMI for at-risk children as part of the regular curriculum in an urban public school setting. Our findings suggest that MMI delivered within the school setting results in decreased behavioral problems and ADHD symptom severity in addition to improved cognitive and motor control.

Limitations and Future Directions

These results should be viewed in light of several limitations, most notably the lack of a control (or active comparison) group and the lack of randomization due to small sample size. Additionally, including multiple mindful movement modalities (Tai Chi, yoga, breathing, imaginative play) in the MMI may present challenges in distinguishing which components may be particularly effective. Future studies should include random assignment to experimental and control groups to confirm that the observed effects are due to the application, as well as address which of the study components (e.g., yoga, Tai Chi) were most effective. Furthermore, the present study included a majority of females, which may bias the results. Future studies should aim to include a more balanced male to female participant ratio. Additionally, due to SARS-COVID-19, precautionary guidance was given to conclude the trial prematurely, thereby limiting the study duration. Therefore, the post-intervention data comes from the mid-point of the study rather than the final time point, potentially yielding relatively reduced effect sizes.

In addition to incorporating randomization, a control group, and longer study duration, future investigations should obtain larger sample sizes including a larger age range, in order to examine potential mediators and moderators of the MMI throughout development. Future studies could also investigate the relationship between the MMI, and additional dimensional characteristics (ADHD traits, measures of motor control and cognitive control, socioemotional development) in addition to potential neural changes, as measured by neuroimaging throughout the study. Furthermore, studies focusing on community/school/group-based MMIs could employ longer follow-up assessment periods in order to validate the efficacy of the intervention following the duration of the active MMI. Additionally, broadening engagement through the MMI with families, teachers, students, and the school community could be beneficial to all parties as well as improve attendance and retention, by providing enhanced understanding and support to students. Finally, in light of the COVID-19 pandemic, multimodal MMI formats should be a concern for future and current studies, as the prospect of hybrid, or virtual delivery of the intervention should be considered to improve continuity of ongoing programs regardless of global health precautionary measures.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12671-022-02063-7.

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Author Contribution LR conducted data analyses and wrote the paper. AD assisted with data analyses and writing. SK assisted with data analyses and writing. KS led mindful movement intervention school collaboration and assisted with study design and implementation. KB assisted with study implementation and writing. KR assisted with data analyses and writing. MJ assisted with study design and development/implementation of the mindful movement intervention program. SM designed study, led mindful movement intervention program, and assisted with data analyses and writing.

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Data Availability The online version contains the mindful movement intervention protocol implemented in this study within the Supplemental Information.

Declarations

Ethics Approval Research ethics approval was obtained from the Johns Hopkins University Institutional Review Board and Baltimore City Public School Institutional Review Board guidelines.

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

Conflict of Interest The authors declare no competing interests.

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