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RESEARCH ARTICLE

Early motor skills predict the developmental trajectory of problem solving in young children with motor delays

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Abstract

Introduction: The purpose of this study was to quantify the relationship between early motor skills, such as sitting, and the development of problem-solving skills in children with motor delays.

Methods: Motor (Gross Motor Function Measure) and problem-solving (Assessment of Problem-Solving in Play) skills of 134 children 7–16 months adjusted age at baseline with motor delay were assessed up to 5 times over 12 months. Participants were divided into two groups: mild and significant motor delay.

Results: Motor and problem-solving scores had large (r's = 0.53–0.67) and statistically significant (p's > .01) correlations at all visits. Baseline motor skills predicted baseline and change in problem solving over time. The associations between motor and problem-solving skills were moderated by level of motor delay, with children with significant motor delay generally having stronger associations compared to those with mild motor delay.

Conclusions: These findings suggest that overall baseline motor skills are predictive of current and future development of problem-solving skills and that children with significant motor delay have a stronger and more stable association between motor and problem-solving skills over time. This highlights that children with motor delays are at risk for secondary delays in problem solving, and this risk increases as degree of motor delay increases.

KEYWORDS
infant, locomotion, motor, posture, problem solving

1 | INTRODUCTION

Motor skills and postural control in the first year of life are thought to be a catalyst for early exploratory play and subsequent academic achievement (Bornstein et al., 2013; Lobo et al., 2013). The theory of embodied cognition states that cognitive development occurs as a result of children's perception–action experiences in the world (Adolph & Hoch, 2019; Smith & Gasser, 2005; Thelen, 2000). Through physical exploration, children gather perceptual information that forms the foundation of their sense of self, understanding of the world, and informs their future actions (Adolph & Hoch, 2019; Smith & Gasser, 2005). As children learn more advanced motor skills, they also gather more complex perceptual information, leading to learning of higher level cognitive constructs such as problem solving. Active and advanced physical exploration at 5 months is an indicator of preschool, elementary, and adolescent academic success (Bornstein et al., 2013; Piek et al., 2008; Viholainen et al., 2006). Pivotal research supporting embodied cognition in children with typical motor development compared the cognitive skills of age matched peers with different motor abilities and experience. Results consistently suggest that motor skill acquisition and experience in different postures influences immediate and long-term development of higher order cognitive skills rather than age alone (Clearfield, 2011; Kretch & Adolph, 2013; Walle, 2016; Walle & Campos, 2014).

From an embodied cognition perspective, children with or at risk for a primary motor delay are also at risk for secondary cognitive impairments (Lobo et al., 2013; Novak et al., 2012). Children with motor delays are also at risk for additional comorbidities such as visual impairment or widespread neurological insults, especially as degree of motor delay becomes more severe (Chokron et al., 2020; Kwong et al., 2018). While there are an unknown number of factors that contribute to children's typical and atypical development, from an embodied cognition perspective, motor skills afford the actions needed to enhance perception and learning despite the presence of other comorbidities (Cicchetti & Toth, 2009 ; Gibson, 1998). Activity and participation limitations due to delayed motor and postural control skills limit the time a child spends acting on the world, thus diminishing their opportunities for learning. Although limited, evidence on embodied cognition in children with or at high risk for a motor delay due to neonatal risk factors indicate that delayed acquisition of motor skills negatively influences cognitive performance (Burns et al., 2004; Needham, 2000; Soska, Adolph, & Johnson, 2010; Walle & Campos, 2014). Delayed attainment of motor skills such as sitting, standing, or walking not only impact concurrent performance on cognitive tests, but more strikingly, delayed motor skills in the first year of life predict poor cognitive outcomes through adolescence and adulthood (Gaysina et al., 2010; Murray et al., 2006).

To expand this body of knowledge, further investigation of the impact of motor delays on cognition is needed (Oudgenoeg-Paz et al., 2017). More specifically, since cognition is a global construct composed of numerous different skills, investigating the impact of motor delays on individual domains of cognition is warranted to understand different mechanisms that may explain the link between motor and cognition (Oudgenoeg-Paz et al., 2017). One cognitive domain that is especially susceptible for delay in children with motor delay is problem solving. The development of problem solving is embodied in motor skills as children use early motor experiences to encounter problems, and to trial and select the most efficient problem-solving solution (Ball & Litchfield, 2013; Horger & Berger, 2019 ; Keen, 2011; Walker & Greenwood, 2010). Assessments of problem solving are used to track a child's readiness for school and to predict later academic achievement (Greenwood et al., 2006; Walker & Greenwood, 2010). Historically, children with motor delay have been identified as demonstrating a lack of readiness to learn in preschool and are more likely to have difficulties in school (Fennell & Dikel, 2001; Gaysina et al., 2010; Orton et al., 2009). Better understanding of the relationship between motor and problem solving can be used to inform early developmental therapeutic services for children with motor delay and help prepare this population for school entry.

The purpose of the current study was to use an embodied cognition approach to quantify the relationship between motor and problem-solving skills in young children with motor delay, including mild and significant motor delay, during the first years of life. The aims were to (1) describe and compare the developmental trajectories of motor and problem-solving skills over 12 months, (2) describe concurrent associations between motor and problem-solving skills, and (3) identify if baseline sitting or overall motor skills predict development of problem-solving skills over 12 months. We hypothesized that all participants would advance their motor and problem-solving scores over time and that children with mild motor delay would have a more positive trajectory compared to children with significant motor delay. Consistent with previous evidence on embodied cognition, we hypothesized that there would be a strong positive correlation between motor skills and problem solving over time and that the relationship would be similar for children with mild and significant motor delay (Houwen et al., 2016; Walker & Greenwood, 2010). Sitting is a frequently cited catalyst for advancing cognitive skills through manual exploration, whereas presitting motor skills such as supine and prone may not afford the same opportunities for exploration as sitting (Lobo et al., 2014; O'Grady & Dusing, 2016; Soska & Adolph, 2014). Since all participants were enrolled when able to sit at least briefly but unable to crawl, we hypothesized that sitting would be a better predictor of problem solving than overall motor skills and that this association would not be moderated by severity.

2 | METHODS

2.1 | Participants

Data were drawn from 134 children of 7–16 months of age (adjusted for prematurity at baseline if applicable), with parents providing written informed consent, who were participating in the control and intervention groups of a large randomized controlled clinical trial (Harbourne et al., 2018). Participants were enrolled in the clinical trial if they scored greater than one standard deviation below the mean on the Bayley Scales of Infant and Toddler Development, Third Edition (BSID-III) gross motor subtest at baseline, demonstrated emerging sitting abilities (defined as the ability to prop sit for 3 s, while unable to transition in and out of sitting independently), and had some active arm movements in sitting (Bayley, 2006; Harbourne et al., 2018). Due to delayed motor skills, most enrolled participants were eligible for and continued to receive early intervention services as part of the Individuals With Disabilities Education Act, Part C throughout the course of this study (Individuals With Disabilities Education Act, 2004). The participants randomized to the intervention group (termed START-Play) received 24, 1-h sessions with a physical therapist over 3 months in addition to any early intervention services received in the community (Harbourne et al., 2018). The START-Play intervention was designed to advance sitting and reaching skills, which then become the building blocks for motor-based problem solving (Harbourne et al., 2018).

Exclusion criteria for the clinical trial included presence of a medical complication that severely limited their participation in assessments (e.g., severe visual disorder), neurodegenerative disorder, diagnosed uncontrolled seizure disorder, or a diagnosis with a known medical/developmental trajectory (Down syndrome, spinal cord injury), per parent report. Participants were recruited through social media, mailings, websites, as well as through medical centers and early intervention providers from five sites across the United States (Duquesne University, University of Delaware, University of Washington, University of Nebraska, Virginia Commonwealth University).

2.2 | Procedure

Participants were categorized into one of two severity groups based on their baseline BSID-III motor composite score. Sixty-eight participants (50.7%) scored between 1 and 2.5 SD below the mean on the BSID-III motor composite score and were allocated to the mild motor delay group, whereas 66 (49.3%) participants scored greater than or equal to 2.5 SD below the mean and were allocated to the significant motor delay group. Reliability of the BSID-III motor composite score was as follows: intra-rater 0.99–1.00 and inter-rater 0.99–1.00. Intervention group assignment for the clinical trial (control vs. START-Play intervention) was completed by stratifying for severity of delay in order to ensure the groups were balanced (START-Play Group: mild motor delay N = 34; significant motor delay N = 33; Control Group: mild motor delay N = 33; significant motor delay N = 34). While the degree of medical impairment was anticipated to be greater in children with significant motor delay, the random group assignment by severity strata was designed to balance any differences in medical status.

Infants were assessed up to five times across 12 months (baseline (0), 1.5, 3, 6, and 12 months post-baseline) using the Gross Motor Function Measure (GMFM; Russel et al., 2013) and the Assessment of Problem-Solving in Play (APSP; Harbourne et al., 2018; Molinini et al., 2021). The assessment schedule was designed as part of the larger clinical trial to examine baseline performance, change during (1.5 months) and immediately following (3 months) a 3-month intervention, and follow-up at 6 and 12 months from baseline (Harbourne et al., 2018). All assessments were completed in the child's home or in a home-like setting in a research lab per the families' request. At least one caregiver was present at each assessment visit. Assessors were blinded to group assignment, trained to reliable administration prior to their first visit, and provided with feedback on administration fidelity throughout the study. All assessments were videotaped for later behavioral coding by coders who were blinded to group assignment and trained to 90% reliability standards.

2.3 | Motor skills assessment

The GMFM is considered the "gold standard" for measuring change over time in gross motor function in children with neuromotor delays (Russell et al., 2002, 2013). The GMFM was administered and interpreted two different ways for this study. (1) The item set of GMFM-66 (GMFM-66-IS) was administered to calculate overall motor skills score and (2) the sitting dimension items of the GMFM-88 (GMFM-SS) was administered to calculate sitting skills scores.

The GMFM-66-IS contains four different item sets. A tool-specific algorithm with decision items was used to identify the appropriate item set for each child during every assessment (Russell et al., 2013). Each item set includes items across five motor dimensions: lying and rolling; sitting; crawling and kneeling; standing; and walking, running, and jumping. The GMFM-66-IS scores demonstrate high reliability evidence (Intraclass Correlation Coefficients = 0.97–0.99) and are responsive to change over time (Wang & Yang, 2006; Wei et al., 2006). Within each dimension, the items are organized from easiest to hardest. Each item is given a score of 0 (does not initiate), 1 (initiates movement), 2 (partially completes the activity), 3 (completed the activity), or NT (item not tested). The total GMFM-66-IS score was calculated via the Gross Motor Ability Estimator-3.

The GMFM-SS score is the summation of raw scores from the 20 items in the sitting domain (i.e., item 18–37) from the GMFM-88. The items were scored on the same 0–3 scoring interval as the GMFM-66-IS but without the option of NT as all items were tested.

During the assessment, assessors would encourage the child to perform each item. The assessment ended when all of the GMFM-SS and GMFM-66-IS items were administered, or the child became too fussy to continue. Parent report was accepted with assessor's observation to ensure that the observed scoring reflected the child's typical abilities as reported by the parent (Russell et al., 2013). Occasionally infants would perform a motor task off camera and the assessor would be unable to recreate this task on camera. In this situation, the assessor would describe the child's specific motor performance on this item on the GMFM score sheet for the coders. Twenty percent of all videotaped assessments were coded twice for ongoing tracking of inter- and intra-rater reliability (ICC = GMFM-SS intra-rater 0.99–1.00, inter-rater 0.97–0.99; GMFM-66-IS intra-rater 0.99–1.00, inter-rater 0.98–0.99).

2.4 | Problem-solving assessment

The APSP is a play-based observational measure developed and validated for use in children with motor delay 7–27 months adjusted age (Molinini et al., 2021). The APSP is adapted from the Early Problem-Solving Indicator, a subtest of the Infant and Toddler Individual Growth and Development Indicators (Greenwood et al., 2006). The APSP is responsive to change over time in children with motor delays and demonstrates strong concurrent validity evidence with the BSID-III cognitive subscale scores (Molinini et al., 2021).

The APSP assessment consists of a child interacting with a set of three toys (popup toy, nesting cups, tower with balls), each for 2 min. During the assessment, the assessor acts as a play partner to the child and provides postural support as needed to allow the child to maintain upright sitting and use his/her arms to interact with the toy. The assessor provides re-direction cues if needed but never provides insight on how to interact with or solve the toy. Using Datavyu v1.3.7, behavioral coders score the videotaped assessments by marking the frequency in which five problem-solving key skills occur. The five problem-solving key skills in order of difficulty include the following:

1. *Look*: A Look is scored when the child gazes at the toy for greater than 3 s.
2. *Simple Explore*: A Simple Explore is scored when the child manipulates the toy to gain knowledge about the object properties, such as mouthing, banging, or scratching.
3. *Complex Explore*: A Complex Explore is scored when the child attempts to execute a function but is unsuccessful, such as attempting to nest a large cup inside a smaller cup.
4. *Function*: A Function is scored when the child completes one step of a toy's function. An example of a function is popping up one animal on the popup toy or nesting one small cup inside a larger cup.
5. *Solution*: A Solution is scored when the child completes all possible functions of the toy. An example of a Solution is popping up and pushing down all animals on the popup toy and nesting or stacking all cups in the correct order.

The problem-solving skills are mutually exclusive and hierarchical in that if they are performing two skills simultaneously, only the highest level skill is recorded. The frequency count of each problem-solving key skill is entered into a weighted scoring model that appoints Look a weight of 1, Simple Explore a weight of 2, Complex Explore a weight of 5, Function a weight of 8, and a Solution has a weight of 16 points (Molinini et al., 2021). Finally, the summed weighted score is then divided by the total assessment time to provide a problem-solving rate per minute score to accommodate for any shortened assessment period. Twenty percent of all videos were scored twice to track inter- and intra-rater reliability. Inter-rater reliability for each problem-solving key skill was ICC = 0.82–0.98.

2.5 | Data analysis plan

Univariate (mean, SD, median, range, percentage) analyses were performed to describe the baseline demographic characteristics of the sample and the motor (GMFM-SS and GMFM-66-IS) and problem-solving (APSP) performance at each visit. Pearson correlation coefficients were estimated to examine the linear zero-order associations between GMFM and APSP scores at each visit aggregating across severity levels and stratifying by severity (Aim 2). Parallel process latent growth curve modeling was performed to describe and compare the developmental trajectories of motor and problem-solving skills (Aim 1) and identify whether baseline and change in GMFM scores predicted baseline and change in APSP scores controlling for baseline prematurity-adjusted age (Aim 3). Higher order polynomial terms (e.g., quadratic growth parameters) were tested and retained only if there was significant evidence of curvilinearity in the trajectories. The models were based on individually varying times of observation to account for variation among participants in the timing of assessments. Separate models were estimated for the two GMFM measures (GMFM-SS and GMFM-66-IS). To evaluate whether severity moderated the trajectories and associations between the GMFM and APSP scores, the same parallel process latent growth curve models were estimated under a multiple group framework such that the parameters were estimated separately but simultaneously for the two severity groups. Data were analyzed in M*plus* Version 8 (Muthén & Muthén, 1998–2017) using full information maximum likelihood estimation with robust standard errors and test statistics. Full information maximum likelihood estimation includes all available data such that subjects were still included in the analyses even if they had missing data at some time points. Statistical significance was set at $\alpha = .05$. Hedges' g and standardized path coefficients were computed to assess practical significance. Age was considered a meaningful factor in contributing to the trajectories of each outcome measure and was controlled for in all analyses (see Supporting Information Appendix Table 1 and Figure 1 for trajectories of motor and problem-solving outcomes by baseline age).

3 | RESULTS

3.1 | Participant demographics and clinical characteristics

The participants with significant motor delay were older, received more early intervention therapy sessions, and had more parent-reported past health concerns at baseline (Table 1). These differences were all expected due to the level of the participants' motor delay. Children with

TABLE 1 Baseline child and family characteristics for the total sample and by baseline motor severity

Variable	Total (N = 134)	Mild motor delay (*n* = 68)	Significant motor delay (*n* = 66)
Sex			
Female	42.5%	42.6%	42.4%
Male	57.5%	57.4%	57.6%
Race			
White	68.2%	69.2%	67.2%
Black	11.6%	7.7%	15.6%
Other	20.2%	23.1%	17.2%
Ethnicity			
Hispanic	15.4%	20.0%	10.8%
Non-Hispanic	84.6%	80.0%	89.2%
Prematurity-adjusted age in months	M = 10.69 (SD = 2.66)	M = 9.62* (SD = 2.14)	M = 11.78* (SD = 2.72)
Gestational age at birth			
≥37 weeks	64.9%	66.2%	63.6%
34–36 weeks	6.7%	11.8%	1.5%
32–33 weeks	7.5%	5.9%	9.1%
25–31 weeks	11.9%	8.8%	15.2%
<25 weeks	9.0%	7.4%	10.6%
Clinical trial group assignment			
START-Play Group	N = 67	N = 34	N = 33
Control Group	N = 67	N = 34	N = 33
Ever had problems seeing	30%	6.2%*	53.8%*
Ever had problems hearing	17.7%	10.8%*	24.6%*
Ever had problems with seizures	23.3%	7.8%*	38.5%*
Ever had brain injury or water on the brain	26.0%	10.9%*	41.3%*
Received early intervention over past 3 months	76.2%	61.9%*	90.5%*
Received private practice intervention over past 3 months	37.1%	35.5%	38.7%
Total frequency of therapy sessions/month over past 3 months	Med. = 4	Med. = 2*	Med. = 6*
Caregiver highest education level		*	*
<HS diploma/GED	1.6%	1.6%	1.6%
HS diploma/GED	12.8%	9.4%	16.4%
Some college, training certificate, or Associate's	25.6%	26.6%	24.6%
Bachelor's	25.6%	15.6%	36.1%
Post-graduate degree	34.4%	46.9%	21.3%
Gross household income	Med. = $60,000–$79,999	Med. = $60,000–$79,999	Med. = $80,000

Abbreviations: Med., median.
*$p < .05$ (significant difference between mild and significant motor delay groups).

more severe motor delays achieve motor milestones later, are more likely to be referred for early intervention (McManus et al., 2020), and are more likely to experience health-related concerns. Of the included participants, 10 were diagnosed with cerebral palsy at some point during the study (one hemiplegia, five tetraplegia, and four spastic cerebral palsy), 24 were diagnosed with unspecified motor delay, and 12 were diagnosed with a global developmental delay of unspecified origin, per parent report. The remaining 88 participants either had no diagnosis or parents did not report a diagnosis.

Comparison of the average scores of the motor and problem-solving assessments at each visit indicate that the mild motor delay group scored significantly higher on the GMFM-66-IS, GMFM-SS, and APSP at all time points (Table 2). On average, the motor abilities of the participants with significant motor delay at the 12-month assessment were

TABLE 2 Average (SD, range) overall motor (GMFM-66 Item Set (IS)), sitting (GMFM-Sitting Scale (SS)), and problem-solving (APSP) scores at each assessment time point

Aggregated	Baseline	1.5 Months	3 Months	6 Months	12 Months
GMFM-66-IS	N = 134	N = 121	N = 124	N = 117	N = 110
	30.89 (5.65, 13.7–42.6)	35.18 (7.70, 18.2–53.6)	38.47 (8.53, 21.1–55.8)	42.67 (11.21, 17.2–60.80)	48.67 (13.82, 17.2–68.7)
GMFM-SS	N = 134	N = 121	N = 124	N = 117	N = 110
	18.36 (8.85, 4–43)	26.5 (13.65, 6–55)	31.86 (15.19, 6–60)	37.67 (18.03, 3–60)	43.31 (18.74, 3–60)
APSP	N = 134	N = 121	N = 124	N = 118	N = 110
	50.7 (26.27, 0.5–127)	57.78 (27.45, 0.83–128)	59 (30.05, 0.5–152.5)	71.24 (37.04, 1.67–152.17)	81.27 (43.82, 2.67–203)
Mild motor delay					
GMFM-66-IS	N = 68	N = 63	N = 62	N = 59	N = 54
	34.38 (4.16, 21.1–42.6)	40 (5.71, 24–53.6)	44.41 (5.57, 36–60.8)	50.61 (6.19, 36–60.8)	58.6 (6.01, 41.5–68.7)
GMFM-SS	N = 68	N = 63	N = 62	N = 59	N = 54
	23.74 (8.51, 9–43)	35.25 (11.45, 9–55)	42 (11.22, 13–60)	49.83 (9.94, 25–60)	55.26 (6.38, 39–60)
APSP	N = 68	N = 63	N = 62	N = 60	N = 54
	64.11 (20.36, 20.83–127)	69.8 (18.18, 29.5–113.33)	70.8 (23.78, 11.67–134.17)	88.99 (29.87, 15.08–152.17)	103.55 (34.63, 21.84–203)
Significant motor delay					
GMFM-66-IS	N = 66	N = 58	N = 62	N = 58	N = 56
	27.28 (4.63, 13.7–37.6)	30 (6.00, 18.2–43.1)	32.54 (6.64, 21.1–47)	34.6 (9.25, 17.2–57.7)	39.15 (12.48, 17.2–65.9)
GMFM-SS	N = 66	N = 58	N = 62	N = 58	N = 56
	12.82 (4.93, 4–29)	17 (8.55, 6–41)	21.76 (11.47, 6–51)	25.29 (15.87, 3–58)	31.79 (19.54, 3–60)
APSP	N = 66	N = 58	N = 62	N = 58	N = 56
	36.87 (24.54, 0.5–92)	44.74 (29.89, 0.83–128)	47.13 (31.14, 0.5–152.5)	52.89 (34.91, 1.67–125)	59.79 (41.15, 2.67–168.5)

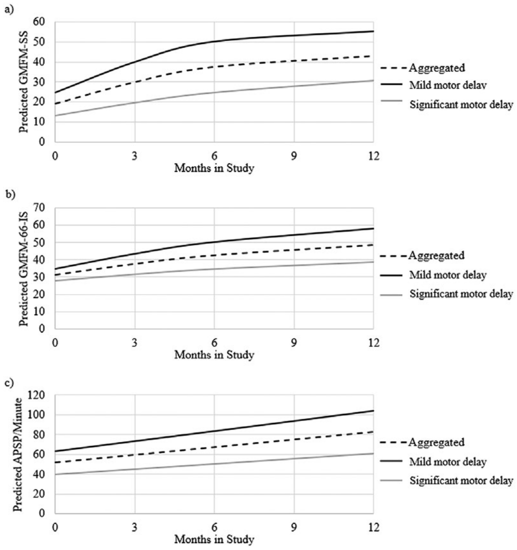

FIGURE 1 Model-predicted trajectories for sitting scores (GMFM-SS; panel a), overall gross motor scores (GMFM-66-IS; panel b), and problem solving (APSP) scores per minute (panel c), aggregating and stratifying by baseline motor severity

comparable to the motor abilities of the mild motor delay group at baseline and 1.5 months post-baseline. Similarly, the average APSP scores of the significant motor delay group at 12 months were less than the APSP scores of the mild motor delay group at baseline.

3.2 | Preliminary analyses considering motor intervention as a moderator

Although not an aim of this study, motor intervention was examined as a moderator to determine whether collapsing across conditions was justified in testing the trajectories of motor and problem-solving skills and the associations between motor and problem-solving skills. Intervention did not moderate any of the associations, thereby justifying collapsing across conditions. In addition, intervention did not account for significant variation as a control variable and was thus omitted from all models (detailed results are presented in the Supporting Information Appendix).

3.3 | Model-predicted longitudinal trajectories of motor and problem-solving skills (Aim 1)

3.3.1 | Aggregating across severity levels

The trajectory of the motor skill assessment scores demonstrated a quadratic trend (GMFM-SS $\hat{b} = -0.18$, SE = 0.02, $p < .001$, $\hat{\beta} = -1.14$; GMFM-66-IS $\hat{b} = -0.08$, SE = 0.01, $p < .001$, $\hat{\beta} = -0.96$) in which the initial linear rate of growth (GMFM-SS $\hat{b} = 4.17$, SE = 0.28, $p < .001$, $\hat{\beta} = 1.58$; GMFM-66-IS $\hat{b} = 2.35$, SE = 0.15, $p < .001$, $\hat{\beta} = 1.58$) significantly decreased over the study period (Figure 1a and b). A significant linear trend ($\hat{b} = 2.61$, SE = 0.23, $p < .001$, $\hat{\beta} = 1.43$) was observed for the APSP scores indicating a constant positive rate of growth over the 12 months study period (Figure 1c). All participants demonstrated significant (p's $< .001$) and positive change over the course of the study period for motor (GMFM-SS mild motor delay: $\hat{M}$ change = 30.37, SE = 1.17; significant motor delay: $\hat{M}$ change = 17.64, SE = 2.13; GMFM-66-IS mild motor delay: $\hat{M}$ change = 23.58, SE = 0.77; significant motor delay: $\hat{M}$ change = 11.17, SE = 1.19) and problem-solving assessments (APSP mild motor delay $\hat{M}$ = 63.63, SE = 1.89; significant motor delay: 39.88, SE = 3.02).

3.3.2 | Severity as a moderator

Compared to children with significant motor delay, children with mild motor delay had significantly greater gains (GMFM-SS $g = 0.86$, $p < .001$; GMFM-66-IS $g = 1.25$, $p < .001$) and higher model predicted baseline scores on the motor developmental assessments (GMFM-SS mild motor delay $\hat{M}$ = 24.85 [SE = 1.12] vs. significant motor delay 13.16 [SE = 0.65], $g = 1.67$, $p < .001$; GMFM-66-IS mild motor delay 34.68 [SE = 0.54] vs. significant motor delay 27.60 [SE = 0.57], $g = 1.60$, $p < .001$) (Figure 1a and b). Children with mild motor delay also showed more positive initial rate of change (GMFM-SS; $p < .001$; mild motor delay: $\hat{b} = 5.891$, SE = 0.29, $p < .001$, $\hat{\beta} = 4.71$; significant motor delay: $\hat{b} = 2.40$, SE = 0.36, $p < .001$, $\hat{\beta} = 0.87$; GMFM-66-IS $p < .001$; mild motor delay: $\hat{b} = 3.26$, SE = 0.18, $p < .001$, $\hat{\beta} = 3.07$; significant motor delay: $\hat{b} = 1.41$, SE = 0.19, $p < .001$, $\hat{\beta} = 1.10$) in the motor developmental assessments but with greater deceleration on average (GMFM-SS $p < .001$; mild motor delay: $\hat{b} = -0.28$, SE = 0.02, $p < .001$, $\hat{\beta} = -2.56$; significant motor delay: $\hat{b} = -0.08$, SE = 0.02, $p < .001$, $\hat{\beta} = -0.58$; GMFM-66-IS $p < .001$; mild motor delay: $\hat{b} = -0.11$, SE = 0.01, $p < .001$, $\hat{\beta} = -1.31$; significant motor delay: $\hat{b} = -0.04$, SE = 0.01, $p = .001$, $\hat{\beta} = -0.57$) than children with significant motor delay.

Compared to children with significant motor delay, problem-solving scores for children with mild motor delay were more favorable at baseline ($\widehat{M}$ = 63.63 [SE = 1.89] vs. 39.88 [SE = 3.02], $g = 1.05$, $p < .001$), demonstrated greater linear change over time ($p < .001$; mild motor delay: $\hat{b} = 3.39$, SE = 0.34, $p < .001$, $\hat{\beta} = 2.03$; significant motor delay: $\hat{b} = 1.77$, SE = 0.28, $p < .001$, $\hat{\beta} = 1.09$), and greater overall growth across the 12 months (mild motor delay: $\hat{M}$ change = 40.62, SE = 4.06, $p < .001$; significant motor delay: $\hat{M}$ change = 21.27, SE = 3.30, $p < .001$; group difference: $g = 0.50$, $p < .001$) (Figure 1c).

3.4 | Correlation between motor and problem-solving skills at the same time point (Aim 2)

3.4.1 | Aggregating across severity levels

Correlations between motor and problem-solving scores are provided in Table 3. Cohen (1988) suggests that $r = .10$, .30, and .50 represent small, moderate, and large correlations, respectively. For the full sample, both the GMFM-SS and GMFM-66-IS scores had significant and strong positive correlations with APSP scores at each time point

TABLE 3 Concurrent correlations between sitting (GMFM-SS) and overall gross motor scores (GMFM-66-IS) and problem solving (APSP) scores across all children (All), children with mild motor delay, or significant motor delay at each visit

	GMFM-SS	GMFM-66-IS
APSP baseline		
All	.57**	.63**
Mild motor delay	.30*	.39*
Significant motor delay	.54**	.50**
APSP 1.5 month		
All	.56**	.62**
Mild motor delay	.30*	.33**
Significant motor delay	.51**	.58**
APSP 3 month		
All	.53**	.59**
Mild motor delay	.16	.23
Significant motor delay	.55**	.63**
APSP 6 month		
All	.64**	.67**
Mild motor delay	.28*	.36**
Significant motor delay	.59**	.62**
APSP 12 month		
All	.63**	.66**
Mild motor delay	.14	.25
Significant motor delay	.60**	.61**

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

(r's = .53–.67). Overall, the associations were slightly stronger for the GMFM-66-IS.

3.4.2 | Severity as a moderator

When stratifying by severity, correlations between motor and problem-solving scores in children with significant motor delay were stronger and more positive than correlations in children with mild motor delay (mild motor delay r's = .14–.39; significant motor delay r's = .5–.63). Correlations were significantly different from zero at all five visits in children with significant motor delay (p's < .001), but only significant at three of five visits in children with mild motor delay (p's < .05) (Table 3).

3.5 | Predictive associations between baseline motor skills and current and future problem-solving skills (Aim 3)

3.5.1 | Aggregating across severity levels

For the full sample, baseline GMFM-SS scores significantly and positively predicted baseline APSP scores ($\hat{b}$ = 1.71, SE = 0.24, p < .001, $\hat{\beta}$ = .72), but did not predict linear change in APSP scores across time ($\hat{b}$ = 0.04, SE = 0.06, p = .494, $\hat{\beta}$ = .20). Baseline GMFM-66-IS scores significantly and positively predicted baseline ($\hat{b}$ = 3.09, SE = 0.33, p < .001, $\hat{\beta}$ = .80) and linear change in APSP scores ($\hat{b}$ = 0.16, SE = 0.06, p = .007, $\hat{\beta}$ = .48), so children with higher overall motor scores at baseline had a greater increase in APSP over time.

Figure 2 shows the model-predicted associations between baseline GMFM-SS (panel a) and GMFM-66-IS scores (panel b) on trajectories of APSP scores, aggregating across baseline motor severity levels. To illustrate the associations, model-predicted APSP trajectories are shown for children who differed by 1 SD in their baseline GMFM scores (−0.5 vs. 0.5 SD from the mean). Level differences in APSP scores are observed as a function of both baseline GMFM-SS and GMFM-66-IS, whereas differences in slope are observed only as a function of baseline GMFM-66-IS.

3.5.2 | Severity as a moderator

The association between baseline GMFM-SS and baseline APSP scores was significantly moderated by baseline motor severity (p < .001), with a stronger association observed for children with a significant motor delay ($\hat{b}$ = 3.59, SE = 0.55, p < .001, $\hat{\beta}$ = .68) than children with a mild motor delay ($\hat{b}$ = 0.60, SE = 0.26, p = .020, $\hat{\beta}$ = .56) (Figure 2, panel c). The association between baseline GMFM-SS and linear change in APSP scores was not moderated by severity (p = .968; mild motor delay: $\hat{b}$ = 0.08, SE = 0.06, p = .148, $\hat{\beta}$ = .40; significant motor delay: $\hat{b}$ = 0.07, SE = 0.18, p = .693, $\hat{\beta}$ = .20).

Likewise, baseline motor severity significantly moderated the association between baseline GMFM-66-IS scores and baseline APSP scores (p = .006; mild motor delay: $\hat{b}$ = 1.51, SE = 0.54, p = .005, $\hat{\beta}$ = .68; significant motor delay: $\hat{b}$ = 3.69, SE = 0.60, p < .001, $\hat{\beta}$ = .69) but not the associations between baseline GMFM-66-IS scores and linear change in APSP scores (p = .349; Mild motor delay: $\hat{b}$ = 0.10, SE = 0.10, p = .295, $\hat{\beta}$ = .25; Significant motor delay: $\hat{b}$ = 0.21, SE = 0.06, p < .001, $\hat{\beta}$ = .56) (Figure 2, panel d).

4 | DISCUSSION

The goal of this study was to quantify the relationship between early motor skills and the development of problem solving in children with motor delays. The results of each aim highlight findings consistent with embodied cognition and carry important implications for professionals working with children with motor delays and their families.

4.1 | Trajectory of motor and problem-solving skills during the first years of life (Aim 1)

Children with mild and significant motor delay's demonstrate clear differences in their motor abilities, and this may have impacted their development of problem-solving skills. Children with mild motor delay

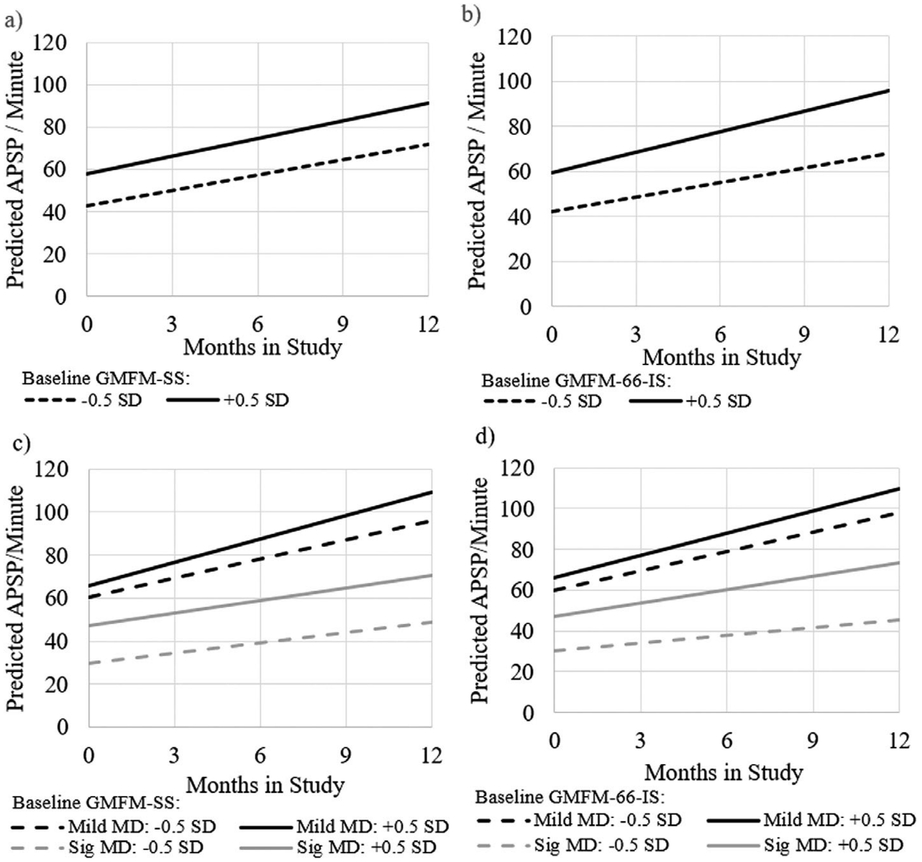

FIGURE 2 Panel (a and b): Model-predicted associations between baseline sitting (GMFM-SS) scores (panel a) and overall gross motor (GMFM-66-IS) scores (panel b) on trajectories of APSP scores. Panel (c and d): Model predicted associations between baseline sitting (GMFM-SS) scores (panel c) and overall gross motor (GMFM-66-IS) scores (panel d) on trajectories of APSP scores in children who performed 1 SD apart on their baseline GMFM scores (±0.5 SD from the mean) within the mild motor delay (mild MD) and significant (Sig MD) motor delay severity groups

increased their sitting (GMFM-SS), overall motor (GMFM-66-IS), and problem-solving (APSP) scores to a greater degree and at a faster rate than children with significant motor delay. While not specifically analyzed, children in the mild motor delay group met the criteria for using item set 3 or higher of the GMFM-66-IS, suggesting they could walk with handheld assistance or independently. In contrast, children with significant motor delay did not meet these same criteria indicating they did not achieve these same skills during the study period. The delay or absence of independent walking limited the dose of exploration and learning that are commonly afforded by independent ambulation (Horger & Berger, 2019; Walle & Campos, 2014). Achievement of and experiences associated with locomotion are consistently associated with higher level cognitive skills, which may have contributed to more positive change in problem solving for the children with mild motor delay (Clearfield, 2011; Kretch & Adolph, 2013).

4.2 | Association of motor and problem-solving skills during the first years of life (Aim 2)

Motor and problem-solving skills of children with motor delays are strongly correlated in the first years of life (Table 3). Contrary to what was hypothesized, severity of motor delay moderated the correlation findings and children with significant motor delay had stronger and more stable correlations across time than the mild motor delay group (Table 3). Houwen et al. (2016) found similar results in that the correlations between motor and cognitive skills in children with a primary intellectual disability increased with severity of delay. Although the participants differed in their primary diagnosis, when taken together, the results from Houwen et al. (2016) and this analysis highlight that as severity of primary delay increases, the strength of the association between motor and cognition also increases. Therefore, it is possible that when a child has a significant delay in one domain, the activity and participation limitations inherent to that delay make the child susceptible to delays in secondary domains creating a global delay. In contrast, a child with a mild delay in one domain may just need time to "catch up" to their peers in that domain and may not be at as high of a risk of developing a global delay. Additionally, children with significant motor delays may have more widespread neurological impairments, which impact multiple regions of the brain contributing to delays in multiple developmental domains.

The correlation findings in children with mild motor delay fluctuated between significant and nonsignificant over the course of 12 months (Table 3). The inconsistent correlations are possibly explained by the relationship between the rate of change of motor and problem-solving skills (Aim 1) and the concept of cognition-action trade off (Figure 1). Cognition-action trade off hypothesizes that as children acquire new motor skills, they allocate their attentional resources to the motor task at the expense of cognition and it is not until they become proficient at a motor task that they can then allocate attention to other tasks. The allocation of attention to motor tasks may be more profound in children with motor delay due to the added difficulty of learning and executing new motor skills in this population (Berger et al., 2018; Harbourne et al., 2014). Harbourne et al. (2014) found that in children with motor delays the motor demands of transitioning from novice to experienced sitter negatively impacted their cognitive performance, but once the child was a proficient sitter they were able to balance motor and cognitive demands in a similar manner as their peers with typical motor development. In our sample, the motor skills (GMFM-SS and GMFM-66-IS) of children with mild motor delay quickly increased at the beginning of the study but then significantly decelerated over time (Figure 1a and b). Although their problem-solving scores demonstrated a constant linear increase over time, with the problem-solving score at each visit being significantly greater than the visit before (Figure 1c). At the 3-month assessment, it is possible that children with mild motor delay were learning and practicing new motor skills at the expense of problem solving. But, by 12 months, they were focusing more on applying their current motor skills to advance problem-solving skills rather than learning new motor skills. Since children with significant motor delay were changing at a slower, linear rate, they were able to balance the cognition-action tradeoff more so than their rapidly changing peers with mild motor delay.

When working with children with any degree of motor delay, cognition-action tradeoff must be taken into consideration during assessment or intervention. There should be a balance of tasks across different developmental domains with the difficulty of tasks matching the goal of assessment or intervention. Likewise, parents may need training on the tradeoff between motor and cognition to understand why their child is able to complete a puzzle when sitting down but may be unable to do the same task once they stand up. An understanding of this balance between advancing motor and cognitive skills can allow caregivers to increase the motor challenge and decrease the cognitive challenge and vice versa to support learning in multiple domains.

4.3 | Early motor skills predict problem-solving (Aim 3)

To evaluate the hypothesis that early motor skills predict the development of problem solving, we analyzed the relationship between baseline sitting (GMFM-SS) or overall motor skills (GMFM-66-IS) to predict baseline and change in problem-solving (APSP) scores over time. In line with our hypothesis, both baseline sitting (GMFM-SS) and overall motor skills (GMFM-66-IS) predicted baseline problem-solving (APSP) scores, and this association was more pronounced for children with significant motor delay (Figure 2). Contrary to our hypothesis that baseline sitting skills (GMFM-SS) would be a predictor of change in problem solving (APSP) over time, we found that only baseline overall motor skills (GMFM-66-IS) predicted the development of problem-solving (APSP) scores, and this relationship was not moderated by motor severity. This suggests that a child with better baseline sitting skills had better baseline problem-solving scores, but they did not necessarily have a more positive trajectory of problem-solving scores over time. However, a child with better overall motor skills at baseline had better baseline problem-solving scores and they had a more positive problem-solving trajectory of time.

A study by Marcinowski et al. (2019) examined a similar association by analyzing the relationship between baseline sitting skills (scored by GMFM-66-IS) and exploration (scored as the frequency of the APSP key skill of simple and complex explores). The participants were recruited as a typically developing comparison cohort to the participants recruited for this analysis. They found that more advanced sitting skills at baseline as scored by the ability to sit without the use of their arms for balance predicted an initial higher rate of exploration during the APSP. Taken together, these results highlight that in children with typical or delayed motor development, better sitting skills at baseline were associated with better concurrent problem-solving skills. Children with better sitting skills are not dependent on their arms for support, thus allowing them to engage in bimanual exploration leading to more opportunities for learning (Libertus & Violi, 2016; Rochat & Goubet, 1995; Soska et al., 2010).

Contrary to our findings, Marcinowski et al. (2019) found that early sitting skills in children with typical motor development uniquely predicted the trajectory of APSP simple and complex explores after baseline. Participants who had higher sitting skills at baseline also had a higher initial rate of change of exploration (problem solving). Due to lack of longitudinal follow up, we do not know if this predictive relationship would have held up over time or if it was only unique to short-term follow up. Interestingly, Marcinowski et al. (2019) hypothesized that if their cohort of children with typical development was followed longer, it is possible that baseline sitting would not be predictive of later problem solving, as any baseline differences in the participants sitting and problem-solving skills were very minimal by 6–8 weeks post baseline. In children with typical motor development, any difference in sitting skill at baseline is likely part of the natural variability of development as evidence by all participants quickly catching up to one another. In this analysis, children with mild and significant motor delay scored differently in their motor and problem-solving skills at baseline and these differences were magnified over time. While the participants with significant motor delay were advancing their sitting skills, those with mild motor delay were already advancing to even harder skills such as crawling or walking. Thus, similar to Marcinowski's hypothesis, it is possible that lack of variability in sitting skills washed out the long-term predictive effect of sitting on problem solving, but because there was widespread variability in overall motor skills, that was still predictive of later problem solving. For both studies, enrolling all children at the same developmental skill level may have resulted in less variability in sitting scores but allowed for greater variability in overall motor scores increasing the validity of the overall motor skills assessment.

The use of the GMFM-66-IS allowed children to display their entire repertoire of motor skills and did not limit their score to only the skills they could perform in sitting. The participants who could perform more dynamic postures at baseline such as commando crawling, rolling, or reaching would have had an increased GMFM-66-IS score but this would not have been reflected necessarily in their GMFM-SS score. The ability to perform dynamic rather than static postures may be more positively related to problem solving in that as children learn these dynamic tasks they must trial different movement strategies until they find the most efficient strategy. The ability to trial solutions that build upon past actions and select the most effective solution is a key pillar to successful problem solving (Ball & Litchfield, 2013; Horger & Berger, 2019 ; Keen, 2011; Walker & Greenwood, 2010). While achievement of sitting is commonly cited as an instrumental position for learning, our results imply that a child's full motor repertoire should be considered during assessment.

4.4 | Limitations

There are several limitations to this study. First, this study is a secondary data analysis of data from a larger clinical trial. Therefore, while the study design afforded the opportunity to complete this analysis, data collection was not planned to address these research questions. More frequent assessment or longer follow up may have provided more insight into the micro- and macrolevel associations of motor and cognition. The inclusion criteria that focused on developmental skill level, although relevant to the intervention and primary outcomes for the original study design, contributed to more variability in participants' ages. The age range at baseline was 7–16 months, meaning that 12 months later those same participants ranged in age from 19 to 28 months old. While this variability in age could explain vast differences in developmental abilities in children with typical development, in the context of our sample population, we do not suspect that variability in age impacted the results. Older age at baseline indicated the presence of a more significant motor delay. Children typically develop emerging sitting skills during the fifth month of life; a child entering this study at 16 months was achieving these skills much later than their peers with typical development and therefore we hypothesize that older age did not benefit these children in the current context (Harbourne et al., 2014). To ensure variability in age did not impact the findings of this analysis, all growth models were controlled for baseline, prematurity-adjusted age. Reliance on parent report for diagnosis and medical history limit the ability to expand findings to specific diagnoses or conditions. More thorough investigation of participant medical history, including neurological imaging, can expand the generalizability of results across different diagnoses. Comparing the results of this study with neuroimaging would provide more insight into the relationship between neurological disorders, motor, and problem solving and provide professionals working with children with motor delays more insight into prognosis and intervention planning based on neurological diagnosis.

Another limitation was that all the participants included in this study were eligible to receive early intervention based on their degree of motor delay. In addition to receiving early intervention, half of the sample received a novel intervention that targeted motor-based problem-solving skills, and thus intervention type or increased intervention dosage may have confounded the results. Since all participants were at the emergence of sitting, it is likely that sitting and reaching skills were a main focus of all therapeutic interventions regardless of whether the child received intervention as part of the clinical trial or early intervention. When studying a clinical population, it is unethical to ask families to discontinue intervention services. To evaluate the impact of intervention type on the current results, we ran additional analyses which highlighted that when aggregating or stratifying by severity, being in the intervention group did not account for significant variability in baseline problem solving skills nor change in problem solving skills.

Finally, the analysis excluded other intrinsic and extrinsic factors that could have contributed to the trajectory of problem solving. Lack of neuroimaging hindered the ability to associate the findings of this analysis with different brain regions. It is anticipated that participants with more significant motor delays would be at risk for more diffuse neurological insults and this could have contributed to the findings. Future studies can include neuroimaging as part of assessment in order to track and identify the association between neurological impairment and development on the relationship between motor and problem solving. Other examples of intrinsic and extrinsic factors excluded from the analysis include physical growth, dosage of intervention received, or type of intervention received. This analysis did not account for the instrumental role that the family plays in both motor and cognitive development. Future research should quantify the effect of type and dosage of intervention and parental impact on the association between motor and cognition.

4.5 | Future research

Although we compared sitting skill versus overall motor skills, we do not know which motor skills specifically correlated to or were associated with change in problem-solving skills. To further the clinical implications of this analysis, it is important to understand which specific motor skills (crawling, walking, etc.) precede and predict change in problem solving. Additionally, including skill matched typically developing children in the analysis can identify if embodied cognition has the same relevance in a clinical versus nonclinical sample. For example, learning to walk has been highlighted as a gateway to advancing receptive and expressive language skills. However, recent findings by West et al. (2019) highlight that learning to walk did not increase language growth in children with an eventual diagnosis of autism spectrum disorder. Understanding the associations and differences of motor and cognition in children with delays or disabilities hold many assessment and intervention implications and further research is warranted.

One advantage of the APSP is that it provides a single summary score that represents a child's problem-solving performance. While this single score is advantageous in analyses such as the one that was performed in this study, it does not provide insight into the mechanism of change in problem solving. By only considering the summary score, it is impossible to know if the change in APSP score was due to an increase in frequency of more rudimentary exploratory skills or a shift toward performing more heavily weighted mature skills. Future research should investigate the relationship of specific motor skills to the emergence of the individual, hierarchical APSP problem-solving skills. This can provide clinical guidance on which exploratory skills need to be a focus of developmental intervention if problem solving is an outcome of interest.

4.6 | Implications

In sum, early motor skills are invaluable in providing opportunities to practice and learn problem-solving skills. Advancing dynamic gross motor skills such as transitioning between static postures, crawling, or walking provide children with variable and complex perceptual information that can advance their problem-solving knowledge and prepare them for academic success. Professionals working with children with any degree of motor delay must be cognizant of monitoring and intervening on their global development as our results indicate that a primary motor delay is associated with a concurrent and future delay in cognition. The results of this study further support the theory of embodied cognition and provide evidence for the fact that motor and cognition become even more interrelated as the degree of motor delay becomes more severe.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AUTHOR CONTRIBUTIONS

Rebecca Molinini: Conceptualization, investigation, writing–original draft, and review and editing. Natalie A. Koziol: Conceptualization, formal analysis, writing–review and editing, and data curation. Tanya Tripathi: Investigation and writing–review and editing. Emily C. Marcinowski: Investigation and writing–review and editing. Lin-Ya Hsu: Investigation and writing–review and editing. Regina T. Harbourne: Conceptualization, writing–review and editing, and supervision. Sarah Westcott McCoy: Conceptualization, writing–review and editing, and supervision. Michele A. Lobo: Conceptualization, writing–review and editing, and supervision. James Bovaird: Conceptualization and supervision. Stacey C. Dusing: Conceptualization, writing–review and editing, and supervision.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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