PHYSICAL ACTIVITY 'ENRICHMENT': A JOINT FOCUS ON MOTOR COMPETENCE, HOT AND COOL EXECUTIVE FUNCTIONS

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Editorial: Physical Activity "Enrichment": A Joint Focus on Motor Competence, Hot and Cool Executive Functions

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Editorial on the Research Topic

Physical Activity "Enrichment": A Joint Focus on Motor Competence, Hot and Cool Executive Functions

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INTRODUCTION

This topic has developed at the crossroads of three scientific paths: (1) physical activity (PA) and cognition research focused on the cognitive challenges involved in PA and motor skill acquisition (Pesce, 2012; Tomporowski and Pesce, 2019; Vazou et al., 2019); (2) developmental neuroscience research looking at PA as one of the means to aid cognitive—especially executive function (EF)—development within a joint physical, cognitive, and emotional framework (Diamond and Ling, 2016, 2020); (3) motor development research that flourished since the publication of Stodden et al. (2008) model and is moving toward a holistic perspective on the role of motor competence (MC) for physical, mental, and socio-emotional health. Thus, these contributions from exercise scientists, developmental neuroscientists, and motor developmentalists address the interconnectedness of PA, MC, cognitive and socio-emotional correlates or outcomes. Here, we integrate the individual contributions into a common framework to discuss current challenges and opportunities and posit implications for future research.

CHALLENGES AND OPPORTUNITIES EMERGING FROM THE CONTRIBUTIONS TO THE RESEARCH TOPIC

Central to this Research Topic is the distinction and integration of "hot" and "cool" EF. Among the top-down neurocognitive control processes that fall under the umbrella term EF and are involved in goal-oriented behavior, the degree of affective and motivational salience have been used to distinguish "hot" and "cool" EFs. The latter are elicited under decontextualized and affectively neutral conditions, as when coping with tasks that require inhibiting interference, playing with ideas in mind, shifting flexibly between cognitive strategies. Instead, "hot" EF processes are performed in affectively salient contexts, as when coping with tasks that involve delaying a gratification/refraining from delay discounting, gambling, or making a risky decision with much to be gained or lost (Zelazo and Carlson, 2012). Studies addressing the MC-EF relation are mainly focused on "cool" EFs, while "hot" EFs are largely neglected (Lakes and Hoyt, 2004; Lakes et al., 2013; Pesce et al., 2020). The literature on "cool" EFs shows a nuanced pattern of selective associations between different facets of MC and EF constructs (van der Fels et al., 2015). Van der Veer et al. show that in preschool children, individual associations weaken when tested as unitary latent constructs of general MC and core EF. The non-linearity of early child development, as well as the "cool" nature of the EF tested, may be responsible for this dissociation. Indeed, Burns et al. found an association in older children between MC and on-task behavior that relies on "hot" EF. However, the strength of this association may be affected by individual and environmental factors, as it was observed in socially disadvantaged children.

The development of MC is "generally" universal and intransitive. It is also cumulative in that the development of skill variations builds a "coordinative pattern toolbox" that can be used at any time. There is no "correct or incorrect" movement *per se*, but rather variations of movement that can be chosen for a specific task goal that is embedded in a particular context. The notion that context-specific experiential learning inherently involves the development and utilization of EF (Pesce et al., 2019) is challenged by an Ecological Dynamics perspective, showing that new creative movement actions may emerge as a result of self-organization tendencies without "cool" EF involvement (Orth et al., 2019). This is the perspective used by Rudd, Pesce et al. to present learner-centered, non-linear pedagogies grounded on "explore-discovery-adapt." The authors propose that "hot" rather than "cool" EFs may be more influential when learners search to utilize "affordances" offered by an enriched environment that has motivational salience and elicits emotional engagement.

PA enrichment and the contextual salience of motor skill learning are central to the contributions by Aadland et al. and Rudd, Crotti et al. which are protocol papers of large-scale interventions in Norway (ACTNOW) and the UK (SAMPLE-PE) with preschoolers and first graders. Both have a 2-fold holistic perspective: they bridge efficacy (i.e., child-level outcomes) and effectiveness research (i.e., evaluation of professional development and implementation processes) and target holistic development in motor, cognitive and socio-emotional domains.

PA enrichment includes both PA enriched with cognitive challenges and cognitive learning tasks enriched with PA. Vazou et al. pilot study tested the feasibility of an intervention with inherent coordinative and cognitive challenges and addresses factors that may indirectly contribute to linked benefits in the motor and EF domains, such as teacher support and motivational climate generated by peers. The other side of the coin is addressed by Damsgaard et al. and Amico and Schaefer. While Darmsgaard et al. used motor activities of low intensity (gestures) relevant to the learning subject, Amico and Schaefer used non-relevant PA tasks of higher intensity (running and dribbling). Both found that adding PA in the encoding phase improved learning in children regardless of its relevance to the learning subject (Mavilidi et al., 2018).

Tomporowski and Qazi address the issue of motor-cognitive dual task effects on memory within a broader, insightful intersection of theoretical perspectives that points to an interactive role of "hot" and "cool" EF. They suggest that bouts of exercise that provide a context for skill development, as those embedded into a learning task may benefit memory storage because they elicit positive affective experiences, engender goal-directed motivated action plans, and maintain mental engagement. However, Jung et al. discuss the limited transferability of dual task research findings to real life. They show the feasibility and cognitive advantage of dual-tasking in a virtual reality environment (Benzing and Schmidt, 2018) that mirrors real-life conditions, underlining the relevance of contextual salience to assess cognitive dual task effects.

The issue of ecological validity of the assessment tasks used to tap dual-task effects and EF is addressed also by Holfelder et al. to explain the absence of differences in "hot" EF between adolescent athletes, who are skilled performers in stable environmental situations (i.e., closed skill sports), or skilled in applying already-learned skills under situational uncertainty and time pressure (i.e., open skill sports). Both sport types may be expected to involve predictive and adaptive control with "hot" and "cool" EF components, yet in different ways. Holfelder et al. found some superiority among open skill athletes in "cool" EFs only, that emerges also as early as childhood, as shown by Moratal et al. The inability to find differences in "hot" EF raises the question of whether it is an issue of insufficient ecological validity of assessments, or insufficient stimulation by the PA and sport training.

"Hot" and "cool" EFs might display joint improvements following sensorimotor activities that are specifically tailored to activate emotional and cognitive states likely linked to brain regions involved in "hot" and "cool" EFs. This is the conclusion drawn by Leshem et al. in their review of neuroscientific evidence on the Quadrato Motor Training, a designed mindful movement training. Since mindful movements have displayed the highest consistency of evidence of EF benefits (Diamond and Ling, 2020), this may be a promising crossroads for research on MC, PA and "hot" and "cool" EFs.

WHAT ARE THE IMPLICATIONS FOR ASSESSMENT AND INTERVENTION?

Enhancing Motor Competence and Executive Function Assessment

A more comprehensive assessment of MC that speaks to "real-world" performance and how it develops across time should include tasks that embody the integration of EFs (that have been developed or are developing) to trigger an optimal solution (i.e., pick the right movement solution from your toolbox) to accomplish the task goal. "Cool" EFs should be assessed by means of performances that are measured not only on a (milli)seconds time scale (Tomporowski et al., 2015) and "hot" EFs by means of responses to challenges in salient physically active or sport game contexts (Lakes, 2013; Pesce et al., 2020).

Adopting a More Contextual Perspective to the Joint Promotion of Motor and Executive Function Development

We also need to attend more carefully to the intervention context. The traditional use of the terms "PA," "exercise," and "dose" by many authors in the public health arena and their linkage to enhanced EF speaks to neural development through mainly metabolic mechanisms that alter the brain structure and function (angiogenesis, neurogenesis). Unfortunately, this lacks an understanding of the contextual specificity of children's movement behaviors (i.e., learning to move and moving to learn) and the related task-specific synaptogenesis pathway in the brain regions involved in the learning task. Indeed, the nature and locus of neural plasticity seem specific to the unique features of the motor experience (Markham and Greenough, 2004; Adkins et al., 2006). Thus, all movement contexts for children should promote a dual focus that synergistically integrates the metabolic and learning (i.e., cognitively and motorically challenging) pathways responsible for angiogenesis, neurogenesis and synaptogenesis in the cortical and subcortical areas involved in EF and motor function to promote synergistic functioning and development (Tomporowski and Pesce, 2019).

To accomplish this, we need to reconceptualize the study and application of developmentally appropriate, holistic movement experiences that promote motor, "hot" and "cool" EF development. This will require a more contextual-specific perspective on emotional and cognitive development promotion, as it exists in the field of psychotherapy outcomes research (Wampold, 2001, 2015). Transitioning this model to PA-cognition research, interventions should directly challenge motoric functioning and EF (specific factors), while indirectly increasing contextual factors that support engagement in the activity (non-specific factors such as social support, joy, motivation), and indirectly decrease contextual factors that impair EF (non-specific factors such as stress, sadness, loneliness).

CONCLUSIONS

Our Research Topic has highlighted the importance of advancing methods of assessment, both in MC and EF domains, and the design and implementation of targeted interventions, embracing a model that pays greater attention to the intervention context and to both specific and non-specific factors that concomitantly contribute to improved MC and "hot" and "cool" EF.

AUTHOR CONTRIBUTIONS

CP developed the initial proposal of the Research Topic. DS and KL provided relevant intellectual content to integrate and refine it. All authors of this Editorial equally contributed to its conception, development and writing, and agree to be accountable for the content of the work.

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BRIEF RESEARCH REPORT
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Gross Motor Skills Predict Classroom Behavior in Lower-Income Children

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Children from lower income families tend to have low levels of on-task behavior in the academic classroom. The purpose of this study was to examine the associations of gross motor skills and classroom behavior in a sample of lower-income children. Participants were a sample of 1,135 school-aged children (mean age = 8.3 ± 1.8 years) recruited from three low-income US schools. A reduced version of the Test for Gross Motor Development 2nd Edition (TGMD-2) was used to assess gross motor skills. Total TGMD-2 scores, locomotor subtest scores, and object control subtest scores were stratified into quintiles for analysis. Students' classroom behavior was recorded 1 year later using a Planned Activity Check (PLACHECK) 5-s momentary time sampling procedure. Classrooms were dichotomized into those that had students at least 80% on-task and those that did not. Multilevel generalized mixed models were employed to examine the relationship between gross motor skills and meeting at least 80% classroom behavior, adjusting for age, sex, and change in BMI, and aerobic fitness. Children in the highest TGMD-2 quintile had 4.17 higher odds of being in an on-task classroom 1 year later (95%CI [2.25–7.76], $p < 0.001$). This relationship was primarily driven by the relationship between object control quintile scores and classroom behavior, as children within the higher quintile for object control had 3.81 higher odds of being in an on-task classroom 1 year later (95%CI [2.67–5.46], $p < 0.001$). There was a significant relationship between individual gross motor skills, specifically object control skills, and group level on-task classroom behavior in lower-income children.

Keywords: behavior, child, gross motor skills, physical activity, schools

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INTRODUCTION

Elementary school children who sit through prolonged academic instruction time can become restless and experience reduced concentration, leading to disruptive classroom behavior (Pellegrini and Davis, 1993). Furthermore, off-task classroom behaviors may lead to reduced memory retention, leading to poorer academic performance (Blankenship et al., 2015). Persistent disruptive behavior may also negatively impact classmates' classroom behavior and academic performance and place unnecessary burdens on academic teachers (Burke et al., 2011). It has been recommended that a classroom should not be off-task for more than 20% of class time to facilitate an optimal learning environment (Rathvon, 2008). Therefore, behavioral strategies to achieve this threshold are important to maintain a classroom environment that is conducive to learning.

School-based programming to improve physical activity has been shown to improve classroom behavior (Mahar et al., 2006; Stylianou et al., 2016). Acute and habitual physical activity may provide a means to moderate psychological arousal by lowering anxiety (Anderson and Shivakumar, 2013) and habitual physical activity may moderate physiological arousal by decreasing stressor-induced cortisol reactivity (Puterman et al., 2011), which may have a positive effect on classroom behavior in children. Studies have shown that physical activity interventions lead to improved classroom behavior in both healthy elementary school-aged children and in children with behavioral health disorders (Bowling et al., 2017; Harvey et al., 2018). Thus, identifying different ways to improve physical activity may be an effective strategy to facilitate better learning environments. Habitual and acute physical activity and exercise may improve attention span and working memory by altering the neurochemicals serotonin, dopamine, norepinephrine, in addition to brain-derived neurotrophic factor, synaptic proteins, and insulin-like growth factor-1 (Winter et al., 2007; Hsieh et al., 2018). Hyperactivity in students and its associated disruptive behaviors in classroom settings may also be attenuated by both habitual and acute physical activity's ability to improve inhibitory control (Berwid and Halperin, 2012). The acute effect of physical activity on neurocognitive function seems to be dose-dependent, in that physical activity and exercise of higher intensities have a more significant beneficial impact on tests of cognitive function (Gonweld et al., 2018). Improving both habitual and acute higher intensity physical activity behaviors and its subsequent links to improved classroom behavior may be facilitated by improving correlates of physical activity.

A correlate of physical activity is gross motor skills (Loprinzi et al., 2015; Burns and Fu, 2018). Fundamental gross motor skills grow from rudimentary phases of infancy to more complicated movements that serve as building blocks for complex movements (Burton and Miller, 1998). In addition to individual age and maturation (Moller et al., 2008), behavioral factors such as physical activity play a role in gross motor skill development. Specifically, higher levels of gross motor skills associate with higher levels of moderate-to-vigorous physical activity (Silva-Santos et al., 2019). Mechanisms for these links include gross motor skills helping children control their bodies, manipulate their environment, and form complex skills involved in sports and other recreational activities (Davis and Burton, 1991). Physical activity interventions have shown to have a positive effect on gross motor skills in children (Robinson et al., 2016). However, conceptual models have proposed and empirical research has shown that gross motor competency also improves habitual physical activity in children, providing evidence for a potential bidirectional relationship between the two constructs (Robinson et al., 2015).

Stodden et al. (2008) proposed a conceptual framework linking improvements in gross motor skills with improvements in physical activity in children and adolescents, which will further lead to decreases in obesity and cardio-metabolic disease risk. Specifically, higher levels of gross motor competency would promote higher levels of physical activity throughout childhood. These relationships lead to a positive spiral of engagement where achievement of a healthy weight would lead to sustained motor competence and maintenance of higher levels of physical activity. Many of these relationships have been empirically tested and may be partially mediated through specific domains of health-related fitness in addition to salient psychosocial variables (Barnett et al., 2008, 2011; Burns et al., 2017). Because motor competence is a primary antecedent in this conceptual model, and because of the established relationships between physical activity with classroom behavior, it is theoretically plausible that higher levels of gross motor skills will also correlate with improved classroom behavior in children. Theoretical mediators of this relationship may be higher habitual physical activity. However, to the authors' knowledge, the correlation between gross motor skills and classroom behavior has not been thoroughly investigated.

A population that can benefit from improved classroom behaviors is children from lower income families. Low family income is associated with poor academic achievement among children (Reardon, 2011). Factors mediating the relationship between low-income status and poor academic underachievement include a lack of support and a lack of a positive learning environment (Banerjee, 2016). Positive learning environments associate with sufficient amounts of on-task classroom behavior (Scott et al., 2007). Furthermore, low income children tend to have lower levels of physical activity (Gordon-Larsen et al., 2006; Jin and Jones-Smith, 2015). As a result, physical activity interventions have been derived with a primary aim to facilitate better academic performance (Centers for Disease Control and Prevention, 2013; Hillman et al., 2014). Because gross motor skills may lead to higher levels of physical activity, and physical activity may lead to better classroom behavior via psychological and physiological arousal modulation, a link between gross motor skills and better classroom behavior is possible but has been largely unexamined within the current literature. Therefore, the purpose of this study was to examine the associations of individual gross motor skills with the probability of a child belonging to a classroom that was sufficiently on-task 1 year later. It was hypothesized that higher levels of individual gross motor skills will associate with a child belonging to a sufficiently on-task homeroom academic classroom 1 year later.

METHODS

Participants

The final sample consisted of participants were a convenience sample of 1,135 school-aged children, which consisted of children with complete data. Children were recruited from the K-5th grades from three low-income schools located in low socio-economic status neighborhoods from the Mountain West Region of the US. A sensitivity analysis for logistic regression was conducted using G*Power which showed that with our sample size ($N = 1,135$), a two-tailed alpha level of 0.05, and power at 80%, the minimum detectable effect is an Odds Ratio = 1.23. All three schools were recruited from the same urban school district. The mean age for the sample at baseline (year 1) was 8.3 ± 1.8 years (Age range: 6–12 years) and there were 569 girls and 566 boys who participated. Age was self-reported from the participants and no exact birthdates were collected. Given the information presented on the school district website, over 78% of the student enrollment at each of the three schools belonged to an ethnic minority, and over 91% of the students were characterized as low-income, receiving free or reduced lunch prices. Low income families are defined by household income that is below twice the federal poverty threshold. In 2015, the federal poverty threshold for a family of four with two children was $24,036. Individual-level race/ethnicity and socio-economic status data was not collected directly from the children. Participant exclusion criteria was any condition precluding child participation in gross motor skill testing and fitness testing. The child also had to be enrolled in one of the three recruited schools for at least 2 years. No special needs children were recruited and special needs classes were not observed for classroom behavior. Written assent and consent were obtained from all observed students and written consent was obtained from the parents prior to data collection. School district approval was also obtained. The University Institutional Review Board approved the protocols employed in this study.

Classroom Behavior Assessment

Classroom behavior data was recorded directly in the classroom setting by both a primary and secondary observer. Time of day, content, and teaching methodology varied across classrooms, and were not controlled for due to classroom observation access scheduling. Students' on-task and off-task behavior was recorded using Planned Activity Check (PLACHECK) 5-s momentary time sampling. Behavioral observations occurred at the end of a 5-s time interval, which commenced after the observer marked the behavior from the immediately prior interval (van der Mars, 1989). Only behavior at the end of a 5-s interval were recorded. Each interval was coded as being on-task or off-task. The primary and secondary observers established the order of observation sequence prior to starting observations. Observations were made from a left to right sequence in the classroom during each observation period, lasting 15 min. Observations commenced 5 min from the start of the lesson. Observers observed a respective student for 5 s before moving on to the next student in the sequence. Students within the sequence were observed multiple times per observation session. A prerecorded audio file signaled the start of each 5-s interval to the observers. Upon hearing the 5-s signals, observers observed and recorded classroom behavior. A primary observer recorded all observations in this study and a secondary observer recorded approximately 50% of the classes with the primary observer to determine interobserver reliability. Inter-observer reliability was calculated by taking the two observers' agreements of on-task behavior and off-task behavior divided by the total number if observations. To obtain a percentage, the agreement proportion was multiplied by 100. The inter-observer reliability was found to be 90%. The aforementioned procedures are in accordance to those recommended by Mahar (2011). Training for the procedures involved having the observers watch a video of a recorded 3rd grade classroom lesson to practice observing and recording behaviors in approximately 15-min intervals. The training was conducted 1–2 weeks prior to the start of data collection. It has been suggested that a classroom should display at or above 80% on-task behavior to sustain an academic environment conducive for optimal learning (Michem et al., 2001). Therefore, classrooms were stratified into those that had at least 80% of the students on-task during an observation period and those that did not.

Gross Motor Skill Assessment

A reduced version of the Test for Gross Motor Development 2nd Edition (TGMD-2) was used to assess gross motor skills (Ulrich, 2000). Because of the time constraints, not all TGMD-2 testing items were assessed during a single 50-min physical education class. One-half (6/12) of the TGMD-2 items were administered. The locomotor subtest items included running, skipping, and leaping. The object control subtest items included throwing, catching, and kicking. Items were chosen based on available gym space and equipment in addition to relevance to common activities engaged in during physical education. Each student performed the test items across two trials that were each scored based on specific performance criteria (0 = did not perform correctly; 1 = performed correctly; Ulrich, 2000). The locomotor and ball subtest scores were both out of 11 and the total TGMD-2 scores were out of 22. The content sampling, time sampling, and inter-scorer differences of the TGMD-2 was determined to be acceptable with coefficients of 0.87, 0.88, and 0.98, respectively (Ulrich, 2000). The TGMD-2 demonstrated good content-description, criterion-prediction, and construct-identification validity evidence using a sample of 1,208 persons in 10 states from the US (Ulrich, 2000).

Health-Related Fitness Assessment

Body Mass Index (BMI) was calculated using standard procedures taking a student's weight in kilograms divided by the square of height in meters (Nuttall, 2011). Height was measured to the nearest 0.01 meters using a portable stadiometer (Seca 213; Hanover, MD, USA) and weight was measured to the nearest 0.1 kilogram using a portable medical scale (BD-590; Tokyo, Japan). Height and weight were collected in a private room during each student's physical education class.

Cardiorespiratory endurance was assessed using the 20-m Progressive Aerobic Cardiovascular Endurance Run (PACER). PACER was administered during each student's physical education class. PACER was conducted on a marked gymnasium floor with background music provided by a compact disk. Each student was instructed to run from one floor marker to marker across a 20-m distance within an allotted time frame. PACER was performed in two sex-specific groups. The allotted time given to reach the specified distance incrementally shortened as the test progressed. If the student twice failed to reach the other floor marker, the test was terminated and the final score was recorded in laps. PACER has shown moderate criterion-related validity scores for predicting aerobic capacity in children (Mayorga-Vega et al., 2015).

Procedures

Gross motor skills were collected during year 1 (Spring, 2015) and BMI and PACER were collected across successive weeks during year 1 and year 2 (Spring, 2015, 2016). A total of 63 classrooms were observed for classroom behavior in year 2 (Spring, 2016). Students from year 1 were matched to a respective classroom during year 2. Homerooms were used for the collection of all classroom behavior data.

Data Analysis

Data were screened for outliers using boxplots and z-scores and checked for Gaussian distributions using k-density plots. To describe the sample, differences between sexes on all observed variables were examined using independent t-tests. Sex difference pairwise comparison effect sizes were calculated using Cohen's delta (d) where $d < 0.20$ indicating a small effect size, $d = 0.50$ indicating a medium effect size, and $d > 0.80$ indicating a large effect size (Cohen, 1988). Predictive utility of TGMD-2 quintile scores on students belonging to classroom that was at least 80% on-task was examined using multilevel generalized mixed effects models. Quintiles were used instead of continuous scores to facilitate interpretation of the odds ratios from logistic regression using the lowest quintile as the reference level. Random intercepts were employed at the school level to adjust for clustering within the data structure. The school random intercept was the only random effect. Fixed effects were the gross motor skill quintile categories and the age, sex, and change in BMI and PACER covariates (potential confounders). Predictors were entered into the model using block-wise entry. The first block (Model 1) consisted of the TGMD-2 quintile scores. The second block (Model 2) consisted of Model 1 plus the potential confounders of age, sex, change in BMI (year 1–year 2), and change in PACER laps (aerobic fitness; year 1–year 2). Reporting of the results consisted of communicating the odds ratios (*ORs*) with 95% Confidence Intervals (95% CIs). For predictors yielding significant effects, marginal probability plots were derived to graphically display the relationships. Secondary analyses were conducted to determine whether the locomotor and object control subtest quintile subtest scores were associated with a student belonging to a sufficiently on-task classroom. All analyses had an initial alpha level of $p < 0.05$ and were carried out using STATA v15.0 statistical software package (StataCorp, College Station, Texas, USA).

RESULTS

Descriptive statistics are reported in **Table 1**. Boys had higher PACER laps at year 1 and 2, TGMD-2 total scores, locomotor subtest scores, and object control scores during year 1 compared to girls. Locomotor skill sex differences were driven by the running test; object control sex differences were driven by all three object control testing items. Sex differences were generally characterized by small effect sizes. Twenty students with complete data at year 1 were lost to follow up at year 2 due to transferring to another school; therefore, classroom behavior data was not collected. Parameter estimates from the generalized mixed effect model are reported in **Table 2**. TGMD-2 quintiles significantly predicted whether or not a student belonged to a sufficiently on-task behavior classroom across all categories (Model 1; $p < 0.05$). This observed significant relationship was held even after adjusting for the potential confounders of age, sex, and change in BMI and aerobic fitness (Model 2; $p < 0.05$). The strongest observed relationship was between children within the highest TGMD-2 quintile having 4.17 higher odds of being in an on-task classroom 1 year later (95%CI [2.25–7.76], $p < 0.001$). This relationship was driven by the relationship between object control subtest quintile scores and classroom behavior, as children within the higher quintile for object control had 3.81 higher odds of being in an on-task classroom 1 year later (95%CI [2.67–5.46], $p < 0.001$). Secondary analyses showed that locomotor subtest quintile scores did not significantly predict a student belonging to an on-task classroom. **Figure 1** displays the marginal predicted probabilities of students belonging to an on-task behavior classroom as a function of TGMD-2 quintile scores. All multilevel models adjusted for the clustering of students within schools.

DISCUSSION

The purpose of this study was to examine the relationship between individual gross motor skills and classroom behavior observed 1-year later in a sample of children from lower-income schools. The results indicated that there is a relationship between individual gross motor skills associating with whether or not a child belonged to a sufficiently on-task classroom 1 year later. Secondary analyses indicated that this relationship was primarily driven by object control scores. Results from this prospective analysis provides information for researchers and practitioners with the aim to improve classroom behavior in lower income children. The results also may direct avenues for additional research examining these relationships via moderated and mediated mechanisms.

The salient finding from the current study was that individual gross motor skills, specifically object control skills, significantly associated with whether or not child belonged to a classroom that was sufficiently on-task 1 year later. Although health-related fitness has been shown to associate with classroom behavior in the pediatric population (Davis and Cooper, 2011; Finn et al., 2018), given the lack of significance in the relationship between BMI and PACER score change and classroom behavior, the relationship between gross motor skills and classroom behavior theoretically may have been mediated by physical activity. What may be important in the observed relationships the type of physical activity engaged in, as previous research has shown that participation in externally paced sports associates with better performance on tests of vigilance capacity, independent of an athletes' level of aerobic fitness (Ballester et al., 2019; Sanabria et al., 2019). The relationship between gross motor skills and physical activity has also previously been established (Barnett et al., 2016). Stodden et al. (2008) developed a conceptual model that clearly links these constructs and specifies the moderating effects of developmental age in the direction of inferred causation. Several studies conducted by Barnett and colleagues support these longitudinal relationships, especially using object control/ball skills subtest scores, possibly because of the high prevalence of locomotor skill proficiency among older children (Barnett et al., 2008, 2011, 2016). Although most studies focus on the links among gross motor skills, physical activity, and health outcomes, a recent systematic review has shown that physical activity effects both gross motor skills and cognitive development in preschool-aged children (Zeng

TABLE 1 | Descriptive statistics (means and standards deviations).

	Total sample (N = 1,135)	Boys (n = 566)	Girls (n = 569)	Sex difference (95% Confidence Interval)	Sex difference Cohen's d
Baseline Age (years)	8.3 (1.8)	8.3 (1.8)	8.3 (1.8)	0.0 (−0.2–0.2)	0.0
Year 1 Height (m)	1.33 (0.14)	1.33 (0.14)	1.33 (0.14)	0.0 (−0.02–0.02)	0.0
Year 2 Height (m)	1.36 (0.11)	1.35 (0.14)	1.36 (0.14)	0.0 (−0.02–0.02)	0.01
Year 1 Weight (kg)	33.7 (13.2)	33.7 (13.1)	33.6 (13.3)	0.2 (−1.3–1.7)	0.01
Year 2 Weight (kg)	33.8 (13.4)	33.7 (13.2)	33.9 (13.6)	1.2 (−2.4–4.7)	0.03
Year 1 BMI (kg/m^2)	18.6 (6.0)	18.6 (6.0)	18.5 (5.9)	0.1 (−0.6–0.8)	0.02
Year 2 BMI (kg/m^2)	17.7 (4.7)	17.6 (4.3)	17.8 (5.1)	0.2 (−0.9–1.1)	0.01
Year 1 PACER laps	24.6 (13.7)	**25.6† (14.7)**	23.6 (12.6)	2.0 (0.4–3.6)	0.15
Year 2 PACER laps	29.8 (18.0)	**31.3† (19.6)**	28.3 (16.1)	3.0 (1.0–5.1)	0.16
Running (out of 4)	3.5 (0.6)	**3.7 (0.6)**	3.5 (0.6)	0.2 (0.1–0.3)	0.17
Skipping (out of 4)	2.5 (0.6)	2.5 (0.6)	2.5 (0.6)	0.0 (−0.1–0.06)	0.0
Leaping (out of 3)	2.2 (0.6)	2.2 (0.6)	2.2 (0.6)	0.0 (−0.1–0.06)	0.0
Catching (out of 3)	2.6 (0.8)	**2.8† (0.7)**	2.5 (0.8)	0.3 (0.2–0.4)	0.41
Kicking (out of 4)	3.0 (0.9)	**3.1† (0.8)**	2.8 (0.8)	0.3 (0.2–0.4)	0.39
Overhead throwing (out of 4)	2.9 (0.8)	**3.0† (0.8)**	2.8 (0.8)	0.2 (0.1–0.3)	0.27
TGMD-2 scores (out of 22)	16.7 (3.8)	**17.2† (3.7)**	16.1 (3.9)	1.1 (0.7–1.5)	0.29
Locomotor skills (out of 11)	8.1 (2.0)	**8.2† (2.0)**	8.0 (2.1)	0.2 (0.02–0.5)	0.11
Object control skills (out of 11)	8.4 (2.2)	**8.8† (2.0)**	8.0 (2.3)	0.8 (0.6–1.1)	0.38

BMI stands for Body Mass Index; PACER stands for Progressive Aerobic Cardiovascular Endurance Run; TGMD-2 stands for Test for Gross Motor Development-2nd Edition; bold and † denotes statistical significance, $p < 0.05$.

et al., 2017). Because of the multifactorial benefits of physical activity on health-related outcomes (Ahn et al., 2018; Tarp et al., 2018), and because physical activity has also shown a beneficial effect on cognitive functioning in children (Castelli et al., 2011; Donnelly and Lambourne, 2011; Donnelly et al., 2016; Bidzan-Bluma and Lipowska, 2018), extending these conceptual models linking gross motor skills to physical activity to variables within the affective and cognitive domains is defensible. Despite this theoretical plausibility, studies examining the relationships between gross motor skills and affective and cognitive outcomes is sparse. It has been found that fine motor skills and executive function can predict kindergartener's academic achievement (Cameron et al., 2012). In younger children aged 3–5 years old, children with better object control manipulation skills in the fall showed significantly stronger social behavior in the classroom in the spring (MacDonald et al., 2016). However, studies showing the prospective link between gross motor skills and classroom behavior in older children are lacking.

Because of the results of the current study and the potential bidirectionality of the relationship between gross motor skills and physical activity, targeting gross motor skill development during health-based programming may potentially elicit improvements in classroom behavior (Lopes et al., 2013). Motor incompetent children suffer from emotional and cognitive issues that reduce quality of life (Cairney et al., 2010). Disengagement in physical activity participation because of the lack of gross motor skills development may also affect health outcomes as motor incompetent children track into adolescence and into adulthood. Unfortunately, lower income children tend to have motor incompetency and may slowly develop specific fundamental skills needed for physical activity engagement (Goodway et al., 2010; Morley et al., 2015; Playford et al., 2017). The results of

TABLE 2 | Fixed-effect parameter estimates and random effects from the multilevel generalized mixed effects model.

		Model 1		Model 2	
		OR	95% CI	*OR*	95% CI
Fixed effects	TGMD-2 1st Quintile	Reference		Reference	-
	TGMD-2 2nd Quintile	**2.32**†	1.59–3.38	**1.98**†	1.34–2.93
	TGMD-2 3rd Quintile	**3.57**†	2.32–5.50	**2.76**†	1.74–4.39
	TGMD-2 4th Quintile	**3.97**†	2.53–6.20	**2.40**†	1.42–4.04
	TGMD-2 5th Quintile	**7.62**†	4.41–13.17	**4.17**†	2.25–7.76
	Baseline Age (years)			**1.32**†	1.18–1.48
	Sex (boy referent)			**1.44**†	1.06–1.94
	Change in PACER laps			0.99	0.98–1.01
	Change in BMI (kg/m^2)			0.99	0.95–1.05
School random effect	Intercept	0.00	0.00–0.00	0.00	0.00–0.00

Model 1 includes the TGMD-2 predictor; Model 2 is the Model 1 and the potential confounding of age, sex, and change in PACER and BMI; OR stands for Odds Ratio; 95% CI stands for 95% Confidence Interval; BMI stands for Body Mass Index; PACER stands for Progressive Aerobic Cardiovascular Endurance Run; TGMD-2 stands for Test for Gross Motor Development-2nd Edition; bold and † indicates statistical significance, $p < 0.05$.

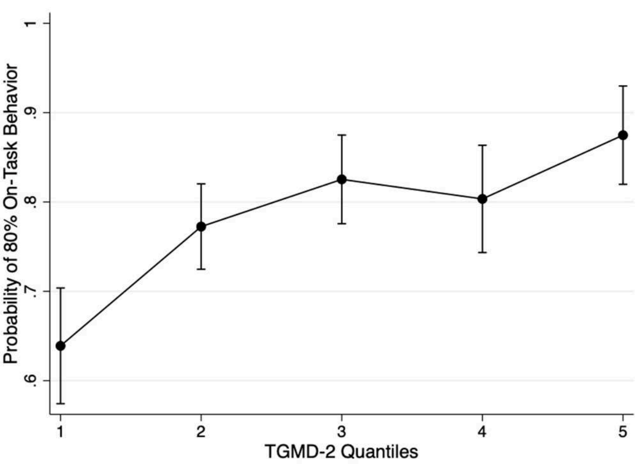

FIGURE 1 | Marginal probability plot showing the relationship between TGMD-2 Quantiles and the probability of a classroom achieving at least 80% on-task classroom behavior. TGMD-2 stands for the Test for Gross Motor Development 2nd Edition; error bars are 95% Confidence Intervals.

this study show that improving gross motor skills may lead to improved classroom behavior in lower income children, which may further lead to improved academic outcomes and overall quality of life.

The results from this study yield avenues for future research. Future research could use accelerometer-assessed physical activity as a mediator variable within the relationship between gross motor skills and classroom behavior. Using accelerometer data, the constructs of sedentary times and physical activity can be analyzed within a time-use approach using compositional data analysis (Burns et al., 2019). This could provide a clearer understanding on the relationships among sedentary times, physical activity, gross motor skills and classroom behavior by dividing time-use behaviors into distinct compositional parts. The relationship between gross motor skills classroom behavior may also be mediated through psychosocial constructs that align with Social-Cognitive Theory and Self-Determination Theory (Barnett et al., 2008; De Meester et al., 2016; Fu and Burns, 2018). The constructs of enjoyment, perceived competence, and self-efficacy may be within the potential causal pathway between gross motor skills and academic classroom behavior. Testing both time-use behaviors (i.e., sedentary times and physical activity) and psychosocial constructs together may provide a more comprehensive approach to understand mediated pathways between gross motor skills and on-task classroom behavior (Stodden et al., 2014). There may also be moderators within these relationships such as socioeconomic status and especially maturation stage that should be explored with additional research as developmental maturation links with both gross motor development, especially ball skills, and classroom behavior. Controlling for factors related to the classroom lesson (e.g., topic, time of day, teaching method, etc.) should also be explored. Finally, collecting motor skill and classroom behavior data on multiple repeated measures time-points across multiple years may provide greater evidence for causation.

There are limitations that should be considered from this study. First, our findings may have limited generalizability because the sample consisted of lower income children recruited from 3 schools from the Mountain West region of the US. Second, the unit of measurement for classroom behavior was analyzed at the classroom level but gross motor skills were assessed at the student level; therefore, caution must be exercised for interpreting findings from this study at the individual level. Third, the data collection was prospective with two time-points, causal inferences may be stronger if a greater number of repeated measures time-points were observed. Fourth, student behavior could have been modified due to the presence of observers within the classroom. Fifth, only chronological age was used as a covariate to control for potential confounding. The use of maturation stage would have been more relevant. Additionally, BMI was also used as a covariate. Use of percent body fat may have been more relevant in younger children (Taylor et al., 1997). Finally, aforementioned moderators and mediators of effect were not tested and should be a priority in future research.

In conclusion, individual gross motor skills, specifically object control skills, related to group level classroom behavior assessed 1 year later in a sample of children from lower income schools. This relationship was independent of child age, sex, and change in BMI and aerobic fitness. Given Stodden's conceptual framework, a possible mechanism for these relationships is the established relationship between gross motor skills and physical activity, which itself is known to correlate with classroom behavior. This study provides some evidence that higher levels of gross motor skills could relate to improved odds of on-task classroom behavior in a sample of low-income children. However, because motor skill data were collected on the individual level and classroom behavior data were collected on the class level, this relationship remains largely speculative. The results potentially provide evidence of the benefits of gross motor skills within the affective and cognitive domains in children.

DATA AVAILABILITY

The datasets generated for this study are available in the **Supplementary Material**.

ETHICS STATEMENT

This studies involving human participants were reviewed and approved by University of Utah Institutional Review Board. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

RB conceived the study, performed the data analysis, wrote the initial draft of the manuscript, and approved the final version of the manuscript to be submitted. WB and TB conceived the study, wrote the initial draft of the manuscript, and approved the final version of the manuscript to be submitted.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2019.00029/full#supplementary-material

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Hot and Cool Executive Function in Elite- and Amateur- Adolescent Athletes From Open and Closed Skills Sports

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Background: Executive functions (EFs) not only play an important role in shaping adolescent's goal-directed, future-oriented cognitive skills under relatively abstract, non-affective conditions (Cool EF), but also under motivationally significant, affective conditions (Hot EF). Empirical evidence suggest a link between EF, exercise and physical activity, specifically elite adult athletes appear to outperform amateur athletes in Cool EF; however, no previous studies have examined the relationship between Hot and Cool EFs and impulsivity during the developmentally sensitive period of adolescence comparing different types of sport (open- vs. closed-skills), and levels (elite athletes vs. amateurs).

Methods: A total 86 boys and girls between 13 and 15 years of age (mean: 14.0, *SD*: 0.79) from different sports (track-and-field; team handball) were recruited. Participants were further divided into two groups: (a) 40 elite, and (b) 46 amateur athletes. They completed four Cool EF tasks including Trail-Making Test, Trail-Walking-Test, Flanker task, n-back-task, and one Hot EF task on Game of Dice task. Data on subjective impulsivity (UPPS Impulsive Behavior Scale; Barratt Impulsiveness Scale-15) was also collected.

Results: There was a significant overall effect for expertise in favor of elite athletes (Wilks' Lambda = 0.61, $F(14,69) = 3.19$, $p = 0.001$, $\eta_p^2 = 0.393$), but no overall main effect for type of sport or an interaction for expertise by type of sport. Specifically, elite athletes showed significantly better performances on dual tasks. For Hot EF, there were no main effects for type of sport, expertise level, training experience or training duration. We also found positive correlations among Cool EF and impulsivity measures, and between Hot EF and Impulsivity, but no significant relationship between Cool and Hot EF.

Conclusion: The current understanding of the decisive cognitive abilities does not correspond to sporting reality, so that the tests frequently used are not sensitive enough to distinguish between elite and amateur athletes or different sports. However, it should also be remembered that the factors underlying complex sporting performance are multidimensional and are obviously difficult to trace back to selected partial aspects. Without being able to answer this question conclusively, we proposed a 4-D classification of experimental paradigms, in which we differentiate between tasks of different specificity, between Cool and Hot EF, and between task complexity, and type of sport.

Keywords: 4-D multicomponent classification model, expertise, impulsivity, Game of Dice task, structural equation model, adolescents

INTRODUCTION

While in the past the athlete's physical ability for explaining sports performance was the main focus, various newer studies have dealt with the interaction of the athlete's physical and cognitive performance, especially in team sports (Vestberg et al., 2012; Furley and Wood, 2016; Montuori et al., 2019). The central issue is how years of practice in different sports affect executive functions (EFs) and whether elite athletes have advantages across different EFs compared to amateur athletes (Voss et al., 2010). To answer this question, it is necessary to consider individual differences in the developmental trajectories of a person and the special features of a particular sport. If one considers the characteristics of team sports such as soccer, which requires a "cool head" for permanent decision-making under time pressure in dynamically changing and unpredictable situations (Huijgen et al., 2015), the relevance of cognitive functions becomes very clear. In this context, it should also be noted that it is not exclusively a matter of cooling the Hot EF. The crucial question is the role of Hot EF in the interaction with Cool EF and their developmental trajectories. In addition, the decision-making behavior of players, in particular toward the end of the game or in tense game situations, is additionally influenced by physical (Smits et al., 2014) and cognitive fatigue (Smith et al., 2016). Depending on the personality structure, these conditions may effect the athlete's self-regulation (Evans et al., 2016) in terms of the motivational level, impulsive and reckless decisions, uncontrolled emotional reactions to a provocation of an opponent (e.g., the head-butt of Zinedine Zidane in the soccer world cup 2006) or violence against referees (Ackery et al., 2012). Further incidents on German football pitches show that violence against referees can no longer be dismissed as isolated actions. All these examples are related to impulsivity and self-control, which seem to pass through a sensitive phase in adolescents (Somerville and Casey, 2010; Zelazo and Carlson, 2012; Casey and Caudle, 2013). They are of great importance in all age groups, and not only in sports (Duckworth and Seligman, 2017). The overgeneralized and deliberately exaggerated statement "Adolescents have no Prefrontal Cortex" (PFC; Casey and Caudle, 2013, p. 3) – a brain area that plays a key role in brain networks underlying EF and self-control (Zelazo and Carlson, 2012; Fiske and Holmboe, 2019) – highlights this point of view.

Regarding individual performance levels, several studies showed that elite athletes outperform amateur athletes and non-athletes in EF (Vestberg et al., 2012; Jacobson and Matthaeus, 2014; Huijgen et al., 2015), but to our knowledge, no study examined both Hot and Cool EF in adolescent athletes. Based on this current state of research and the relevance described above, this study examines Hot and Cool EFs during the developmentally sensitive period of adolescence comparing different types of sport (open- vs.- closed skills), and levels of expertise (elite vs. amateur athletes).

Hot and Cool Executive Functions: What Are They?

Self-regulation is a general ability to focus one's attention on relevant aspects, to regulate current emotions, to suppress urgent impulses and to control behavior in a targeted and situation-adapted way (Diamond, 2013). One research strand deals mainly with the cool, cognitive aspects of self-regulation. These include cognitive psychology – with its main representative Baddeley (2000) and Baddeley et al. (2019) – and neuropsychology with Miyake et al. (2000). On the other hand, a temperament based "Hot" approach deals predominantly with the emotional-motivational aspects of self-regulation (Rothbart and Bates, 2006; Eisenberg et al., 2010; Zhou et al., 2012).

The EF's, too, are a collective term, under which a broad spectrum of cognitive abilities are summarized, which are always needed when one wants to deviate from familiar everyday routines (Friedman and Miyake, 2017). On the one hand, this includes complex processes such as planning and monitoring the results and objectives of one's own actions. More frequently, however, basal cognitive abilities are examined, whereby three EF are usually used, which Miyake et al. (2000) postulate: (1) Inhibition describes the ability to suppress predominant reaction tendencies; (2) Updating describes the processes of continuous monitoring and updating of working memory contents, and (3) Shifting includes the ability to change mentally between different tasks. The tripartite factor structure found by Miyake et al. (2000) in their student sample has already been reproduced several times in young adults (e.g., Ito et al., 2015), older adults (e.g., Vaughan and Giovanello, 2010), children and adolescents (e.g., Rose et al., 2012; Lee et al., 2013; Usai et al., 2013; Brydges et al., 2014).

In addition to these "Cool," cognitive EF, Effortful Control forms the "Warm/Hot," emotional-motivational second component of self-regulation. Effortful control is understood by Rothbart and Bates (2006) as the ability to suppress dominant responses and/or activate less dominant responses. According to this definition, the term Effortful Control should be equated with the construct of self-regulation *per se* or with EF (Diamond, 2013). Such an equation, however, does not do justice to the use of the terms in many studies. Effortful control is more often understood as self-regulation concentrated on emotions and motivations, in contrast to an executive self-regulatory component focused on cognitive processes (Zhou et al., 2012).

Zelazo and Müller (2002) introduced a similar distinction between a cognitive and an affective component in 2002 – albeit in relation to EF: they described the cognitive processes required for abstract tasks as "Cool EF" and the regulation processes in affect-loaded situations as "Hot EF." Following this terminology, the cognitive facet of self-regulation is referred to as "Cool" EF and the emotional-motivational component as "Hot" Effortful control.

EF and Effortful Control were mostly researched separately due to the different research directions. Only few studies have investigated both aspects together in a sporting context (Hongwanishkul et al., 2005; Prencipe et al., 2011; Lensing and Elsner, 2018; O'Toole et al., 2018), or they focus on special populations outside the sport context (e.g., ADHD: Geurts et al., 2006; Antonini et al., 2015; Skogli et al., 2017; Autism Spectrum Disorder: Zimmerman et al., 2016; Kouklari et al., 2017; childhood obsessive-compulsive disorder: Hybel et al., 2017). While measures of Cool EF are strongly correlated, Poon (2018) found no significant relationship between Hot and Cool EF measures in a group of 12 to 17-year-old boys and girls outside the sports context. Furthermore, from a current review there is little support for significant sex differences in Cool EF (Grissom and Reyes, 2019).

Role of Executive Functions in Elite Sport

The distinction between open- and closed-skills sports seems to be an interesting approach for differentiated statements on the relationship between athletic performance and the performance in EF (Wang et al., 2013a; Tsai et al., 2017). Closed skills are characterized by relatively stable environmental conditions and repetitive movement patterns, as is the case with swimming or jogging. Skills that are predominantly executed in sports such as team handball, soccer, fencing or tennis, which require a constant adaptation to changing and unpredictable environmental conditions as well direct interactions with opponents, are referred to as open-skills sports (Nuri et al., 2013; Huijgen et al., 2015; Elferink-Gemser et al., 2018). Therefore, executing open skills in a functional context requires a high level of visual attention, the ability to make quick and flexible decisions, and fast movement execution (Taddei et al., 2012; Tsai et al., 2016). Thus, sports with predominantly open skills are cognitively more demanding than sports with closed skills. This leads to the assumption that athletes from sports with open skills who are constantly confronted with these cognitive stimuli should have better sport relevant cognitive performance (Voss et al., 2010; Rigoli et al., 2012; Tsai and Wang, 2015; Elferink-Gemser et al., 2018). This assumption is countered by studies in which closed-skills sports such as endurance running and cycling lead to significant improvements in EF (c.f. reviews, Sibley and Etnier, 2003; Barenberg et al., 2011; Fedewa and Ahn, 2011). For example, Wang et al. (2013a) examined inhibitory control (stop-signal task) with n = 60 male students (n = 20 tennis players, n = 20 swimmers, n = 20 sedentary controls). The tennis players achieved significantly shorter reaction times compared to swimmers and sedentary controls, while there were no significant differences between swimmers and sedentary controls. It should be noted, however, that it is methodologically difficult to clearly distinguish between open- and closed-skills sports, since in, e.g., soccer, in addition to the open skills, closed skills are also used, which underlines the importance to control for confounders like the fitness level or training hours (Wang et al., 2013b; Elferink-Gemser et al., 2018).

With regard to the current state of research on EF in sports, studies focused in particular on athletes of open-skill sports such as table tennis (Elferink-Gemser et al., 2018), ice hockey, rugby (Faubert, 2013), track-and-field (Schott and Krull, 2019), and soccer (Vestberg et al., 2012, 2017; Verburgh et al., 2014, 2016; Huijgen et al., 2015) with the focus on the comparison of Cool EF in elite and sub-elite (amateur) athletes. Although "[. . .] there is no hard evidence that expert athletes have superior basic cognitive abilities compared to normal, physically active controls [. . .]" (Elferink-Gemser et al., 2018, p. 2), the aforementioned studies as well as two meta-analytic reviews (Voss et al., 2010; Scharfen and Memmert, 2019) concluded, that the level of athletic performance and the type of sport have a positive effect (with small to medium effect-sizes) on multiple subdomains of cognitive functions (Cool EF), based on non-sport specific tests.

While for Cool EF many studies confirm these findings, little is known about the significance of Hot EF in the sports context. This is the case, although Hot EF play an important role in situations, where decisions with emotional consequences need to be made and the emotional processes controlled (Kelley et al., 2015; Stein et al., 2017). Decision-making as a central feature of sports situations requires a constant control of impulses (Wang et al., 2013a), and the regulation of impulsivity (González-Hernández et al., 2019) in order to filter out the relevant information in emotionally arousing and complex situation under time pressure, and to weigh the risk of different solutions with the greatest prospect of success. On the one hand, emotions have an important influence on athletic performance (Kopp and Jekauc, 2018), but a certain level of positive emotional arousal also contributes to athletic performance (Palazzolo, 2019). On the other hand, it is known from research on decision-making that the decision-making process can be impaired in emotionally arousing situations, especially among adolescents (van Duijvenvoorde et al., 2010). Adolescence, in turn is characterized by sensitivity to impulsivity (Leshem, 2016) and challenging phases of emotion regulation (Young et al., 2019), that promote risky behavior (Hartley and Somerville, 2015), which is more pronounced in boys (Cross et al., 2011; Romer et al., 2017). Although impulsivity is multidimensional and decision-making is a complex process, there appears to be a close interaction in adolescence. In this regard, Romer (2010) and Romer et al. (2017) respectively subdivide impulsivity into the three forms *sensation seeking*, *impatience* and *acting without thinking*, the last two being related to low EF. Fino et al. (2014) also confirm the interaction between impulsivity and EF by showing that impulsivity is a predictor of EF in college students. In particular, *acting without thinking*, also known as motor impulsivity (Romer et al., 2009), seems to be important in sports, as it means a weak ability to consider different alternatives in, e.g., complex game situations or to be "mindless" at a party the night before an important competition. In addition, the relevance of *impatience* is given when a player has to decide between a fast, but risky shot at the goal or a trained tactically smart move in interaction with the teammates.

Romer et al. (2017) suggest the interaction of experience and brain development, e.g., the PFC and brain networks in this area as an important reason why adolescents react sensitively to impulsivity and tend to make more thoughtless and risky decisions. This is in accordance with the understanding of an experienced-based development of EF (Müller et al., 2013). It should be noted that many findings support the understanding of a sensitive phase in adolescents on a structural, functional and behavioral level. However, Romer et al. (2017) emphasize, that impulsivity varies from individual to individual and some conclusions drawn are the result of the stereotype "[...] the adolescent as impulsive and lacking in cognitive control" (Romer et al., 2017, p. 24).

In summary, despite the importance of Hot and Cold EF in sports, there are no studies to date that have investigated the association between Hot and Cold EF in young athletes. Therefore, the goal of this study was to investigate possible differences in Hot and Cool EF between close- skills sports (track-and-field) and open-skills sports (team handball), taking into account performance level (elite vs. amateur) and sex. Based on what we know from previous studies, we hypothesized that elite athletes would show better results than amateurs in both Cool and Hot EF. Regarding the sport type, we assume that open-skills sport athletes outperform closed-skills sport athletes in cognitive performance and that the differences between elite athletes and amateurs are less pronounced in the open-skill sports. Taking into account the findings on the sex-specific development of EF, impulsivity and risk taking behavior (Cross et al., 2011; Romer et al., 2017; Grissom and Reyes, 2019), we do not expect significant differences between girls and boys in Cool EF, but we do expect significant differences in Hot EF.

MATERIALS AND METHODS

Participants

A total of 86 boys and girls between 13 and 15 years of age (mean age: 14.0, *SD*: 0.79) participated in the current study. Of these, 19 adolescents are elite team handball players (competing at the D-regional-squad and D-national-squad) and 27 age-matched amateur team handball players with handball experience of 3 to 13 years, practice of 1–5 days a week for 90 to 120 min. Twenty-one track-and-field athletes from the D-national-squad were included in the elite group, and another 19 age-matched subjects competed on an amateur level. The track-and-field group had an overall experience of 2 to 13 years, practice on one to five times a week for 90 to 120 min.

Instruments

This subsection will describe the instruments used in the present study. Hot EF were assessed using the Game of Dice Task (GDT; Brand et al., 2005). Miyake et al. (2000) suggest that working memory, inhibition, and cognitive flexibility are three central aspects of EF. Based on this, we decided to assess Cool EF with a n-back task (Yun et al., 2010), a modified Flanker-task (Schott and Krull, 2019), the Trail-Making-Test (Reitan, 1958), and the Trail-Walking-Test (Schott, 2015). Two established self-report measures of impulsivity, the UPPS Impulsive Behavior Scale (Whiteside and Lynam, 2001) and the Barratt Impulsiveness Scale (BIS-15; Patton et al., 1995) were also administered.

Cognitive Measures

The *Game of Dice Task* (GDT; Brand et al., 2005) was used to measure decision making under risk. Participants are asked to maximize their fictive starting capital of €1000 within 18 dice throws. Subjects bet which number will be thrown by a single dice in order to maximize their starting capital. The bet can be placed on a single number or on a combination of two, three, or four numbers. Each choice is associated with fictive gains and losses depending on the probability of the occurrence of the choice: €1000 gain/loss for the choice of a single number (winning probability 1:6), €500 gain/loss for two numbers (winning probability 2:6), €200 gain/loss for three numbers (winning probability 3:6), or €100 gain/loss for four numbers (winning probability 4:6). Participants receive feedback (gain or loss) for their previous decision in a visual way, and the changed capital is shown. To analyze the risky decision making, we classified the choices of three or four number combinations as "non-risky" (winning probability of 50% and higher), and the choices of one or two numbers as "risky" (winning probability of less than 50%). We calculated a net score by subtracting the number of risky choices from the number of non-risky choices, as done in several other studies that used this task. A positive net score indicates advantageous choice behavior (range: −18 to 18).

We used the *n-back task* introduced by Yun et al. (2010). Each subject was given trials grouped in blocks, with 36 trials/block. Each trial consisted of a visual presentation of a letter for 500 ms followed by an interstimulus interval of 1500 ms. Subjects were instructed to press a target button as soon as possible for each trial in which the letter shown was the same as the letter shown n trials previously, and to press a non-target button otherwise. For the 0-back, targets were each occurrence of the letter "a." Target responses were set to occur with 50% frequency, with accuracy computed as the number of correct responses divided by the number of trials. Subjects were given blocks of 0-back, 1-back, and 2-back. They were instructed to perform the tasks to the best of their ability, emphasizing accuracy over reaction time when possible.

Inhibition was assessed by performance during a *modified flanker task* (Eriksen and Eriksen, 1974; Schott and Krull, 2019). The stimuli were presented using E-Prime software (Psychology Software Tools, Inc., Pittsburgh, PA, United States) on a 17-in computer monitor. Responses were registered using a standard QWERTZ keyboard. Participants sat approximately 70 cm away from the screen. During the task, participants attended to a centrally presented target stimulus (Chinese letters) amid an array of laterally presented flanking stimuli. During the compatible version of the task (all signs point in to the same direction; 不不不不不), participants were required to press "L." During the incompatible condition (不不不不不, participants were required to press "S." Five letter stimuli, measuring 4.5 cm tall and separated by 1 cm were presented for 750 ms on a white background. Participants were instructed to ignore the outside letters and to respond only to the central letter. A randomized inter-stimulus interval of 400 to 1200 ms was used, and both the number of trials within each condition and the frequency of target direction were equiprobable, with randomly presented trials within each task block. Participants were administered four blocks of 32 trials for each compatibility condition and given a brief break and encouragement between each block. For all analyses, individual trials with RT's outside the 200–1650 ms post-stimulus onset window and incorrect trials were excluded from the RT analysis (Wu et al., 2011).

The *Trail-Making-Test* (TMT; Reitan, 1958) was used to assess EF. The reliability and validity of the TMT are well-established. The paper and pencil test consists of two parts. Part A requires the serial connection of numbers (1 to 25) randomly distributed on a white sheet of paper. Part A (TMT-A) assesses attention, visual scanning, motor speed and coordination. During part B (TMT-B), participants are asked to connect randomly positioned numbers (1 to 13) and letters (A to L) in an ascending number-letter sequence (1-A-2-B- etc.). The TMT-B assesses mental flexibility and working memory in addition to the abilities assessed by part A (Bowie and Harvey, 2006). The trials were timed using a stopwatch to the nearest 0.01 s. Due to the longer total trail length of TMT B compared to TMT A (Gaudino et al., 1995) we report the speed (cm/s) instead of the total duration. Additionally, we used a difference score (TMT-B-A) calculated by subtracting TMT-A from TMT-B. The TMT-B-A/A score is used to adjust the test time by the common motor speed element, resulting in a more accurate measure of the complex processes of cognitive flexibility and set shifting unique to TMT-B (Corrigan and Hinkeldey, 1987). These newly calculated variables represent the so-called Dual Task Effects (DTE).

To examine mobility and at the same time the use of cognitive skills such as visual scanning, vigilance, attention, and problem solving we used a dual task test. The *Trail-Walking-Test* (TWT; Schott, 2015) is based on the idea of the paper-and-pencil Trail Making Test, participants walk along a fixed pathway (TWT A), step on targets with increasing sequential numbers (i.e., 1-2-3; TWT B), and increasing sequential numbers and letters (i.e., 1-A-2-B-3-C; TWT C). Cones with numbers and/or letters are placed randomly at each of the 15 positions in a 16-m2 area (4 m × 4 m). A 30-cm diameter circle was drawn around each cone. Passage was considered to be successful when the participant stepped on the circle around the cones. The trials were timed using a stopwatch to the nearest 0.01 s following a standard procedure. The TWT was performed three times in each condition. Similar to the procedure of the TMT, the DTE were also calculated for TWT A and TWT B. To ensure consistency and to minimize errors, all trials of the TMT and TWT for all athletes were stopped by the research assistant.

Impulsivity Measures

The *UPPS Impulsive Behavior Scale* (Whiteside and Lynam, 2001, German version Schmidt et al., 2008) distinguishes between four dimensions of impulsivity: (1) urgency, the tendency to act rashly under conditions of negative or positive effect (12 items), (2) premeditation, the tendency to reflect on the consequences of an act before engaging in that act (11 items), (3) perseverance, an individual's ability to remain focused on a task that may be boring or difficult (10 items) and (4) sensation seeking (12 items), the tendency to enjoy and pursue activities that are exciting and openness toward novel experiences that may be dangerous. Each item on the UPPS is rated on a four-point scale ranging from 1 (strongly agree) to 4 (strongly disagree). For each facet, higher scores indicate a higher level of impulsivity. The final questionnaire consists of 45 items and the factor structure was validated with confirmatory factor analysis. The German version of the UPPS scale in this study shows also reliable (Cronbach's α: urgency 0.76; Premeditation 0.76; perseverance 0.77; sensation seeking 0.81) and valid acquisition of the hypothesized impulsivity facets (Kämpfe and Mitte, 2009).

The *Barratt Impulsiveness Scale-15* (BIS-15; Spinella, 2007; German version Meule et al., 2011) is a scale that has been used to assess psychological profiles and emotional regulation in risk taking sports (Cazenvae et al., 2007), and professional fighters (Banks et al., 2014). The BIS-15 is 15-item a self-report measure that is rated on a four-point scale from 1 (rarely/never) to 4 (nearly always/always), with composite scores ranging from 15 to 60. The measure assesses various aspects of impulsivity on three scales: (a) attentional impulsiveness (5 items), defined as a tendency toward quick reactions and lack of attention and cognitive control; (b) motor impulsiveness (5 items), measuring behavioral spontaneousness such as buying things spontaneously, and (c) non-planning impulsiveness (5 items), describing a lack of action planning on the level of a general attitude toward life, such as a low interest in one's future. Moderate internal consistency has been found for the BIS-15 in this study (Cronbach's α: non-planning impulsivity 0.67; motor impulsivity 0.67; attentional impulsivity 0.57); validity support exists with EFs (Spinella, 2007).

Procedure

Prior to inclusion in the study, all participants signed an informed consent form. All assessments were conducted in accordance with ethical rules for research in human subjects following the Declaration of Helsinki (Edinburgh, 2000), World Medicine Association[1]. Subjects were assessed in one session; all participants started with the neuropsychological assessment, followed by the questionnaire measures. To avoid effects of the testing order within the neuropsychological assessment, two different testing orders were applied (Hot EF testing at the beginning vs. at the end). Participants were allocated randomly and counterbalanced. No significant influence of the testing order was observed. The session was conducted on a comfortable adequately illuminated room. The session had an approximate duration of 60 min. All tests were administered by a research assistant.

Data Analysis

Statistical analyses were implemented on SPSS v.25 and AMOS 25.0 (SPSS, Chicago, IL, United States). We first explored dependent variables to examine missing data points, normality

[1] http:www.wma.net

of distributions (tested by Kolmogorov–Smirnov tests), and presence of outliers.

A 2-vector scoring procedure of the flanker-task as well as the n-back-task, which uses both accuracy and reaction time, was applied on the basis of NIH Toolbox system (National Institutes of Health Toolbox Cognition Battery [NIH Toolbox CB], 2013), where each of these "vectors" ranges in value between 0 and 5. The accuracy score is calculated by 0.15625 (Flanker) or 0.1388 (n-back) points multiplied by the number of correct responses. The median reaction time values are generated using only trials with correct responses. Identical to the accuracy scores, reaction time scores range from 0 to 5 points. Because reaction time data tends to have a positively skewed distribution, a log (Base 10) transformation is be applied to each participant's median reaction time score to create a more normal distribution of scores. The minimum RT for scoring was set to 400 ms for the Flanker and 300 ms for the n-back task, and the maximum RT for scoring is 800 ms for the Flanker task and 1300 ms for the n-back task. The following formula was used for rescaling:

$$Flanker\ RT\ score = 5 - \left(5 \times \left[\frac{logRT - \log(400)}{\log(800) - \log(400)}\right]\right)$$

$$n - back\ RT\ score = 5 - \left(5 \times \left[\frac{logRT - \log(300)}{\log(1300) - \log(300)}\right]\right)$$

After the RT scores are calculated, they are combined with the accuracy scores. If a participant's accuracy scores are less than 80%, the final calculated score is equal to the accuracy score. However, if the accuracy score is greater than 80%, the accuracy and response time scores are combined. The calculated score combines the two vector scores and is between 0 and 10.

To determine effects of type of sport and expertise level on performance on the cognitive tasks, univariate ANCOVAs were used with sex, training experience, and training duration as covariates. Where a significant effect was found, subsequent simple contrasts (elite athletes vs. amateurs, open-skills sport vs. closed-skills sport) were performed. We used Bonferroni correction to control for multiple comparisons, resulting in corrected alpha level of 0.004 (i.e., 0.05/12).

A structural equation model was created to examine the relationship between Hot and Cool EF and impulsivity, which was calculated using AMOS 25.0. The most robust method, the maximum likelihood method, was used as the estimation model (Tabachnick and Fidell, 2013). In order to investigate the structure of the overall model and to determine the overall variance explanation contribution (R^2), due to the large number of predictors, only those variables were included from each predictor group that could make a significant explanation contribution in their respective predictor group. Following the Tabachnick and Fidell (2013), several indices are used as model fit indices. In detail, these are the Chi-square statistics, the Tucker Lewis Index (TLI) and Bentler's Comparative Fit Index (CFI). A statistically significant chi-square test value is to be taken as an indication of poor model fit. For the other indices, a good fit is assumed for values above 0.90 (see Hu and Bentler, 1995).

RESULTS

Participants

Regarding the variables of the sports biography, we found significant differences in sporting experience between the skill groups as well as expertise level in terms of years of training [SPT: $F(1,82) = 15.2$, $p < 0.001$, $\eta_p^2 = 0.156$; E: $F(1,82) = 10.8$, $p = 0.001$, $\eta_p^2 = 0.116$] and training duration [main sport; SPT: $F(1,82) = 5.89$, $p = 0.017$, $\eta_p^2 = 0.067$; E: $F(1,82) = 71.5$, $p < 0.001$, $\eta_p^2 = 0.466$]. In addition, a significant difference between the sports type was found for training duration in additional sports [$F(1,82) = 8.62$, $p = 0.004$, $\eta_p^2 = 0.095$], which is defined as the average value (min/week) of up to three other sports. Furthermore, there was a significant difference for expertise level for BMI percentile [$F(1,82) = 12.5$, $p < 0.001$, $\eta_p^2 = 0.132$], but not for the type of sport. No individuals reported having a history of neurological problems or cardiovascular diseases, nor were any taking any medications that affect cognitive functions. **Table 1** summarizes the participant's characteristics.

Cognitive Measures

The Game of Dice Task

Inspection of the GDT net score ranges indicated that especially athletes from track-and-field performed poorly (i.e., negative net score with a majority of disadvantageous choices). Twelve participants from closed-skills sport (30%), but only eight open-skills sport athletes (17.4%) had a negative net score on the GDT.

A 2 × 2 ANCOVA computed for the GDT netscore as dependent variable and type of sport and expertise level as independent variables controlled for sex, training experience, and training duration revealed a significant main effect of sex [$F(1,79) = 6.96$, $p = 0.010$, $\eta_p^2 = 0.081$], indicating an advantageous choice behavior in girls (8.56 ± 8.09) compared to the boys (3.72 ± 8.81). A trend toward a significant interaction was found for type of sport by expertise level, [$F(1,79) = 3.00$, $p = 0.087$, $\eta_p^2 = 0.037$]. **Figure 1** indicates no differences between amateurs and elite athletes from open-skills sport in contrast to a poorer performance of amateurs compared to elite athletes from closed-skills sport. There were no main effects for type of sport, expertise level, training experience or training duration.

N-Back Task

Scores on the 0-back, 1-back, and the 2-back task are plotted in **Figure 2**. Repeated measures ANCOVA computed for the n-back scores as dependent variables and type of sport, expertise level as independent variables controlled for sex, training experience, and training duration revealed a significant main effect for task difficulty, [$F(1.50,118) = 11.6$, $p < 0.001$, $\eta_p^2 = 0.128$]. *Post hoc* tests demonstrated that scores were highest in the easiest task, the 0-back task (8.75 ± 1.34), and lowest for the hardest, the 2-back task (2.81 ± 1.37). Additionally, we found a significant influence of training experience on n-back task difficulty, [$F(1.50,118) = 3.46$, $p = 0.044$, $\eta_p^2 = 0.042$], indicating better working memory performance with a higher number of years of training experience. There were no effects for type of sport, expertise level, sex or training experience across the three

TABLE 1 | Group means (± SD) of the characteristics of the open skills sport players, and the closed skills sport athletes according to their expertise level.

	Closed-skills group (Track-and-Field)		Open-skills group (Team handball)		Statistical analysis		
	Amateur *n* = 19	Elite *n* = 21	Amateur *n* = 27	Elite *n* = 19	SPT	E	SPT x E
Age (years)	14.2 ± 0.79	13.5 ± 0.68	14.0 ± 0.81	14.1 ± 0.74	ns	ns	*
Sex	10 M, 9 F	10 M, 11 F	12 M, 15 F	11 M, 8 F	ns	ns	ns
Height (cm)	168 ± 8.57	171 ± 8.21	168 ± 7.67	170 ± 8.17	ns	ns	ns
Weight (kg)	54.9 ± 9.95	58.9 ± 10.3	54.3 ± 8.61	61.1 ± 10.3	ns	*	ns
BMI (kg/m^2)	19.3 ± 2.43	20.0 ± 2.35	19.1 ± 1.92	21.2 ± 2.20	ns	**	ns
BMI percentile	44.5 ± 23.9	57.0 ± 23.3	43.8 ± 22.0	65.4 ± 18.8	ns	***	ns
Training experience (years)	5.11 ± 2.13	6.76 ± 2.39	7.07 ± 1.52	7.63 ± 1.57	***	***	ns
Training duration main sport (min/week)	254 ± 101	472 ± 102	228 ± 83.7	390 ± 130	*	***	ns
Training duration additional sport (min/week)	36.3 ± 67.5	65.2 ± 76.3	18.9 ± 37.3	11.1 ± 33.5	**	ns	ns

*SPT, sport type; E, expertise; *p < 0.05; **p < 0.01; ***p < 0.001.*

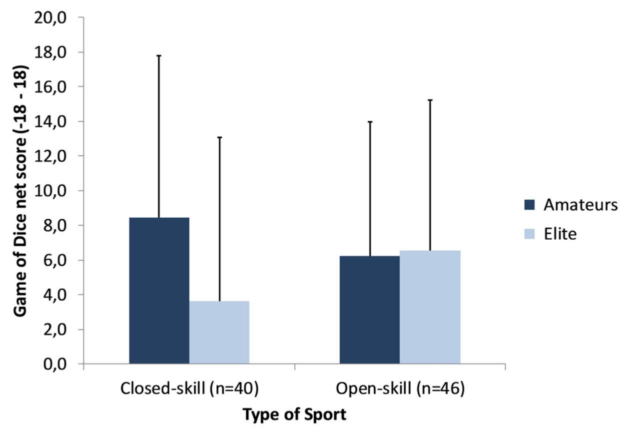

FIGURE 1 | The Game of Dice Task: net differences scores (advantageous choices–disadvantageous choices; mean, SD) across amateur and elite athletes from closed- and open-skills sports.

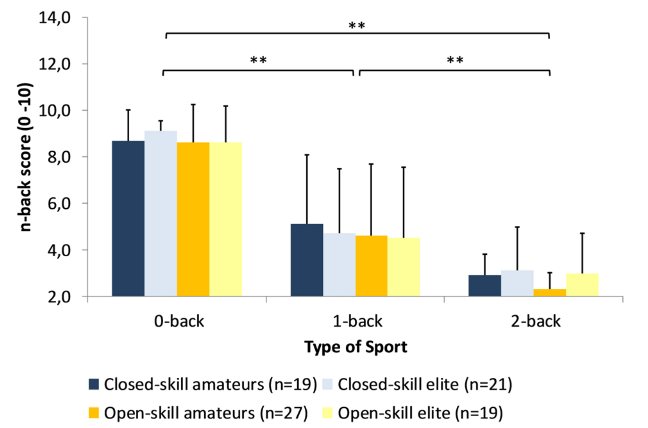

FIGURE 2 | Performance of the composite score on the n-back Task as a function of expertise and type of sport (**$p < 0.01$).

conditions. The reaction times and accuracy for the n-back Task is presented in **Supplementary Figure S1**.

Flanker Task

Scores were submitted to a 2 × 2 mixed-model ANCOVA, with condition (congruent or incongruent) as within-subjects factors, and type of sport and expertise level as between-subjects factors controlled for sex, training experience, and training duration. We found no main effects for condition, type of sport or level of expertise: athletes from the open-skills group were not faster than athletes from closed-skills group; elite athletes were not faster than amateurs (see **Figure 3**). No effects were found for sex, training experience, and training duration. The reaction times and accuracy for the Flanker Task is presented in **Supplementary Figure S2**.

Trail-Making-Test

Repeated measures ANCOVA computed for the TMT A and TMT B times as dependent variables and type of sport, expertise level as independent variables controlled for sex, training experience, and training duration revealed a significant main effect for task difficulty, [$F(1,79) = 8.04$, $p = 0.006$, $\eta_p^2 = 0.092$] indicating longer durations on the more difficult task. *Post hoc* analysis showed a significant main effect of sex for TMT A [$F(1,79) = 6.06$, $p = 0.016$, $\eta_p^2 = 0.071$] as well as TMT B [$F(1,79) = 6.17$, $p = 0.015$, $\eta_p^2 = 0.072$], indicating better performances in girls (TMT A 9.86 ± 2.46; TMT B 5.38 ± 1.43) compared to boys (TMT A 8.66 ± 2.23; TMT B 4.71 ± 1.23). There were no main effects for expertise, type of sport, training experience, and training duration, nor were there any interaction effects for expertise level by type of sport (see **Figure 4**). Furthermore, no significant main effects or interactions could be found for the DTE.

Trail-Walking-Test

Repeated measures ANCOVA computed for the TWT walking speeds as dependent variables and type of sport, expertise level as independent variables controlled for sex, training experience, and training duration revealed a significant main effect for task

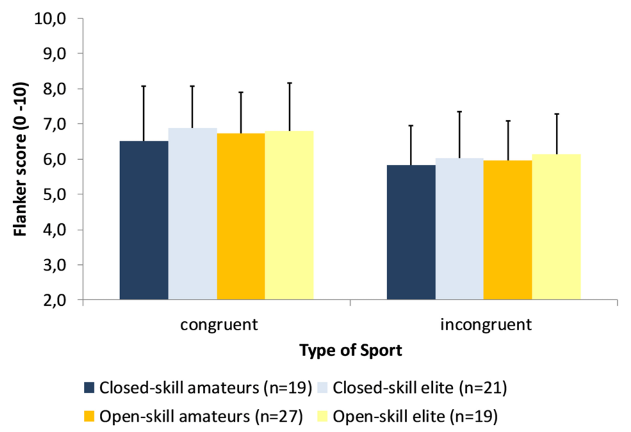

FIGURE 3 | Performance of the composite score on the Flanker Task as a function of expertise and type of sport.

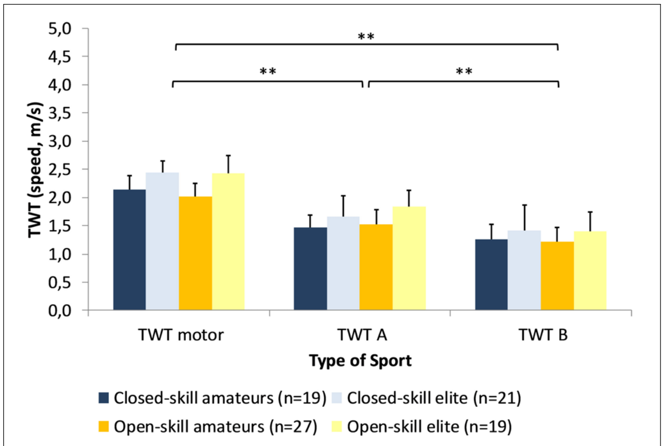

FIGURE 5 | Performance of the Trail-Walking-Test (mean, SD) as a function of expertise and type of sport (** $p < 0.01$).

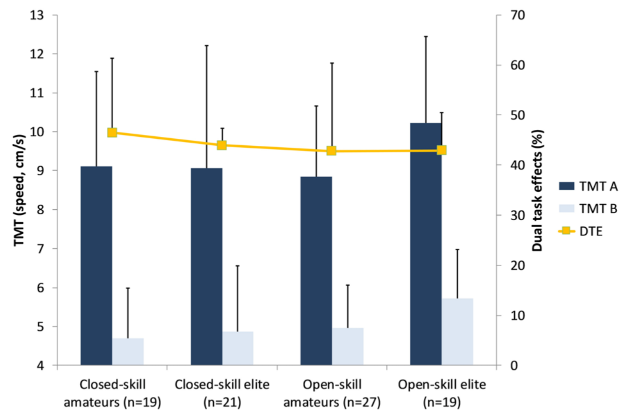

FIGURE 4 | Trail-Making-Test (mean, SD), and DTEs across athletes from closed- and open-skills sports.

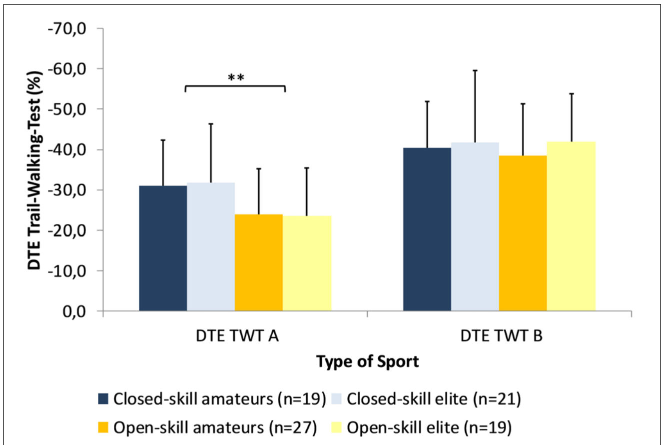

FIGURE 6 | Dual Task Effects for the Trail-Walking-Test as a function of expertise and type of sport (** $p < 0.01$).

difficulty, [$F(2,158) = 20.4$, $p < 0.001$, $\eta_p^2 = 0.205$]. *Post hoc* tests demonstrated that speeds were highest in the easiest task, the Trail-Tracing-task task (2.24 ± 0.31 m/s), and lowest for the hardest, the TWT B task (1.32 ± 0.33 m/s) (see **Figure 5**). In addition, there was a significant task difficulty by sex interaction, [$F(2,158) = 5.49$, $p = 0.005$, $\eta_p^2 = 0.065$], indicating that boys outperform girls but only in the easiest condition. We also found a significant task difficulty by type of sport interaction, [$F(2,158) = 6.60$, $p = 0.002$, $\eta_p^2 = 0.077$] showing that athletes from open-skills sports outperform athletes from the closed-skills group, but only in the TWT B. Further *post hoc*-tests showed significant effects for the level of expertise with elite athletes outperforming amateurs in all three conditions (TWT motor: 2.43 ± 0.26 vs. 2.06 ± 0.25; TWT A: 1.75 ± 0.34 vs. 1.50 ± 0.24; TWT B: 1.41 ± 0.39 vs. 1.24 ± 0.25).

Repeated measures ANCOVA computed for the DTEs of the TWT A and B as dependent variables and type of sport, expertise level as independent variables controlled for sex, training experience, and training duration revealed a significant main effect for task difficulty, [$F(1,79) = 4.98$, $p = 0.028$, $\eta_p^2 = 0.059$]. *Post hoc* tests demonstrated that DTEs were higher for TWT B (−40.5 ± 13.6) compared to TWT A (−27.3 ± 12.7). In addition, there was a significant interaction task difficulty x type of sport, [$F(1,79) = 7.77$, $p = 0.007$, $\eta_p^2 = 0.090$], showing similar DTEs for the TWT B (−39.9 ± 12.4 vs. −41.1 ± 14.9), but lower DTEs for the athletes from the open-skill group (−23.8 ± 11.4) compared to the closed-skill group (−31.3 ± 13.1) (see **Figure 6**).

Impulsivity

Scores from the dimensions "non-planning impulsivity," and "motor impulsivity" of the BIS-15 proved unrelated for type of sport and expertise level (see **Table 2**). However, an ANCOVA showed a main effect of sex with boys scoring higher than girls on the subscale attentional impulsivity (10.0 ± 2.37 vs. 9.0 ± 2.12; [$F(1,79) = 6.32$, $p = 0.014$, $\eta_p^2 = 0.074$]). Furthermore, an ANCOVA revealed a significant type of sport by expertise interaction for the Barratt Attentional subscale [$F(1,79) = 7.85$, $p = 0.006$, $\eta_p^2 = 0.090$] with elite athletes from closed-skills sport

TABLE 2 | Group differences in impulsivity measures.

	Closed skills sport (track-and-field)		Open skills sport (team handball)		Statistical analysis			
	Amateurs *n* = 19	**Elite athletes *n* = 21**	**Amateurs *n* = 27**	**Elite athletes *n* = 19**	**S**	**SPT**	**E**	**SPT x E**
BIS-15								
Non-planning impulsivity (5–15)	11.8 ± 1.85	12.1 ± 2.30	12.7 ± 2.35	11.2 ± 3.19	ns	ns	ns	ns
Motor impulsivity (5–15)	10.6 ± 2.57	11.9 ± 2.86	11.3 ± 2.51	11.2 ± 2.23	ns	ns	ns	ns
Attentional impulsivity (5–15)	8.74 ± 2.75	10.2 ± 2.47	10.1 ± 1.92	8.84 ± 1.83	*	ns	ns	***
Total (15–60)	31.1 ± 5.16	34.1 ± 5.54	34.1 ± 4.14	31.3 ± 5.61	ns	ns	ns	***
UPPS								
Urgency (1–48)	26.4 ± 5.38	27.4 ± 4.15	28.5 ± 5.66	29.5 ± 4.01	ns	ns	ns	ns
Premeditation (1–44)	25.0 ± 4.43	26.7 ± 4.09	27.9 ± 4.45	26.4 ± 4.51	ns	ns	ns	ns
Perseverance (1–40)	20.1 ± 3.95	19.7 ± 3.96	22.0 ± 4.52	21.8 ± 4.75	ns	ns	ns	ns
Sensation seeking (1–48)	35.8 ± 5.18	38.5 ± 5.60	36.8 ± 6.34	38.6 ± 6.01	**	ns	ns	ns

*S, sex; SPT, sport type; E, expertise; *p < 0.05; **p < 0.01; ***p < 0.001.*

showing higher attentional impulsivity than amateurs while elite athletes in open-skills sport exhibit lower attentional impulsivity than amateurs. The same type of sport by expertise interaction was found for the Barratt total score [$F(1,79) = 7.78$, $p = 0.007$, $\eta_p^2 = 0.090$]. Following Cohen's interpretation of effect sizes (Tabachnick and Fidell, 2013) the effect size of group differences for the interaction was medium for attentional impulsivity and the total score.

2 × 2 ANCOVAs with the covariates sex, training experience, and training duration were used to detect whether means for type of sport and expertise level were significantly different on the UPPS scales. Boys scored higher on sensation seeking than girls did (39.2 ± 5.26 vs. 35.6 ± 6.00; [$F(1,79) = 7.93$, $p = 0.006$, $\eta_p^2 = 0.091$]). Elite athletes did not differ significantly from amateurs, nor were there any differences between athletes from open-skills and closed-skills sports.

Relationship Between Impulsivity, Hot and Cool Executive Function

The structural equation model is shown in **Figure 7**. Standardized regression weights are shown for associations between each variable. Poor impulsivity was associated with disadvantageous choices, yet impulsivity was not correlated with Cool EF. Associations between Hot and Cool EF did not meet the significance threshold. A non-significant chi square ($\chi^2 = 1.35$, $p = 0.114$), the goodness-of-fit indicators (CFI = 0.932, TLI = 0.901, SRMR = 0.07, and RMSEA = 0.064) revealed that this model had a good fit, with a reasonable number of degrees of freedom (DF = 25).

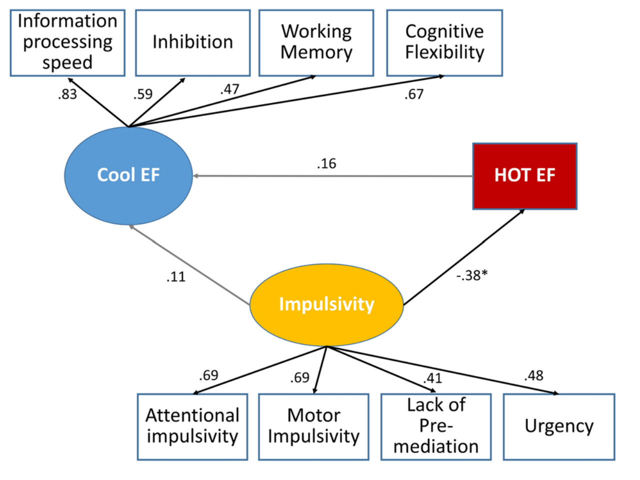

FIGURE 7 | Proposed causal paths of Hot and Cool EF and Impulsivity (standardized solution) for all athletes (*n* = 86).

DISCUSSION

Discussion of Results

The purpose of this study in adolescents was to examine possible differences in Hot and Cool EF between closed-skills sport (track-and-field) and open-skills sport (team handball) athletes taking into account their performance level (elite vs. amateurs) and sex.

There are a number of studies showing that elite athletes are superior to amateurs in various perceptual cognitive tasks (e.g., Voss et al., 2010; Scharfen and Memmert, 2019), but without being able to present corresponding consistent findings to date (Elferink-Gemser et al., 2018). Regarding the Cool EF, the elite athletes in our study outperform the amateurs in all TWT conditions. Additionally, a significant influence of training experience on the working memory performance was observed, indicating better results with a higher number of training years. There are no significant differences between elite athletes and amateurs, neither for the flanker nor for the n-back task. These results are partially in line with our expectations and are not comparable to the findings of other studies in this field that compared performance in cognitive tests assessing Cool EF between expert and amateur athletes. For example, in the study by Huijgen et al. (2015), adolescent elite soccer players outperform sub-elite soccer players in inhibitory control and cognitive flexibility, but not in working memory or metacognition. The highly talented soccer players in the study by Verburgh et al. (2014) achieve better results in motor inhibition compared to the amateur soccer players, but not for visuospatial working memory, orienting and executive attention. One explanation for these inconsistent results could be that the sport-specific cognitive stimulation in sports are superimposed by other cognitive stimuli in school or recreational activities that enhance EF (Diamond and Lee, 2011; Diamond and Ling, 2016; Finch, 2019). This understanding seems particularly likely in children and adolescents, as sport is not practiced as a profession and thus competes with many other stimulants. All of this takes place at life stages in which the development of the brain is particularly dynamic (Fuhrmann et al., 2015; Nelson et al., 2016). Regardless of the type of sport, there are no significant differences between amateur and elite athletes with regard to Hot EF in the Game of Dice Task. Also for the two questionnaires investigating subjective impulsivity, no significant differences were observed for either sport type or level of expertise.

With regard to the two different types of sport, there are two significant effects for the Cool EF. One for the TWT B and the other for the DTEs in the TWT A, whereby in both cases the athletes from the open-skills sport achieved better results. These findings are in accordance with our hypothesis and the findings of previous studies in students (Wang et al., 2013a) and elderly (Tsai and Wang, 2015; Tsai et al., 2017), that athletes from open-skills sport outperform athletes from closed-skills sport. Again, the results are not as clear-cut as expected. Looking at the characteristic of the open-skills sport team handball, i.e., continuous memorization and situational application of individual and team tactical behavior in interaction with fellow players and the opposing team, cognitive skills such as mental flexibility and working memory are fundamental (Debanne et al., 2014; Furley and Wood, 2016).

For impulsivity, as measured by the UPPS Impulsive Behavior Scale no significant results were found for sports type, expertise or their interaction after controlling for covariates sex, training experience, and training duration. Apart from this, the significant type of sport by expertise interactions remain difficult to interpret for the Barratt total score and the subscale attentional impulsivity. The higher values for attentional impulsivity scores for the elite athletes compared to the amateur closed-skills-sport athletes do not confirm our hypothesis and are only partially comprehensible. It is possible that this finding can be explained by the significant differences between the type of sports due to the training duration in additional sports, with higher values for the closed-skills sport elite athletes (c.f. **Table 1**). It can therefore be assumed, that these athletes are confronted with more variable stimuli in different sports context, which may not result in such a clear cognitive profile. This assumption is supported by the overall higher standard deviations of the closed-skills sport athletes for the attentional impulsivity scores (c.f. **Table 2**). Finally, the structural equation model used to examine the interaction between Cool EF, Hot EF and impulsivity did not result in a significant relationship between Hot and Cool EF (see **Figure 7**).

Furthermore, no significant correlations were observed between assessments for Cool EF and Hot EF/impulsivity (see **Supplementary Table S1**). Thus, our findings confirm the results of Poon (2018), who found no significant relationship between Hot and Cool EF measures in a group of 12 to 17-year-old boys and girls. However, our results do not confirm the findings of Fino et al. (2014), that impulsivity is a predictor of EF. With regard to the question why there is no influence of sports type and performance level, several explanatory approaches be worth considering. First, the frequently cognitive measures used may not be specific enough to identify possible sport-related cognitive improvements, or, conversely, improved sport-specific cognitive abilities may be too specific to be transferred into cognitive measures from within the sports context (Voss et al., 2010; Faubert, 2013; Jacobson and Matthaeus, 2014). Furthermore, according to Poon (2018), the development of Cool and Hot EF during adolescence is characterized by different age-related patterns, with Hot EF developing more slowly (Prencipe et al., 2011; O'Toole et al., 2018). Finally, it can be assumed that the current understanding of the decisive cognitive abilities does not correspond to sporting reality, so that the tests frequently used up to now are not sensitive enough to distinguish between elite and amateur athletes or different sports.

A decisive question is whether a certain cognitive performance level is responsible for people performing above average in certain sports or if sport-specific training shape sport-specific cognitive profiles (chicken or egg dilemma; e.g., Voss et al., 2010; Jacobson and Matthaeus, 2014; Verburgh et al., 2014). This view is supported by the fact that even within one sport, different roles lead to or require specific cognitive profiles in order to be successful in this position (Montuori et al., 2019). The current state of research does not allow a clear answer, but it can be assumed that both perspectives are mutually dependent. In childhood, the choice of sport is often made according to what is on offer in the city or the choice depends on friends, parents, or role models (Maturo and Cunningham, 2013; Morgenroth et al., 2015). Finally, there is no doubt cognitive functions are fundamental and play a key role in sports performance, so our results addressing type of sport and expertise should be interpreted with caution.

Already Voss et al. (2010) have designated sex as an overall moderator on cognitive measures. Nevertheless, most studies in this field investigated only males (e.g., Wang et al., 2013a,b; Verburgh et al., 2014; Vestberg et al., 2017) or did not report sex-specific results (e.g., Jacobson and Matthaeus, 2014; Elferink-Gemser et al., 2018), possibly because they were not significant or meaningful. With regard to our results regarding the influence of sex on Cool EF there are a few significant differences between girls and boys, but no clear and meaningful findings were observed. These results are not only consistent with our hypothesis, but also consistent with previous studies (Vestberg et al., 2012; Grissom and Reyes, 2019).

Looking at the results of the Hot EF, girls achieved significant higher net scores in the GDT, indicating a more favorable choice behavior in girls and a more risky behavior in boys. In addition, boys scored significant higher on the BIS-15 subscale attentional impulsivity, indicating a greater propensity for rapid responses, lack of attention and cognitive control. These findings are supported by the UPPS Impulsive Behavior Scale results, which show significant higher scores for sensation seeking in boys. Therefore, the results partially confirm our hypothesis and are in accordance with previous studies (Cross et al., 2011; Romer et al., 2017).

Explanatory approaches to sex differences may be found from insights of neuroanatomical studies. Giedd and Rapoport (2010) report that sex-specific developmental trajectories for almost all structures are known. In girls, the maximum gray matter is reached 1–3 years earlier than in boys. According to Tanaka et al. (2012), brain volume and gray matter in the frontal and parietal lobes of girls develop faster than in boys, but linearly until adolescence. The cerebellar, frontal and parietal lobes are areas most often associated with EF (see systematic review of Nowrangi et al., 2014). Also in the study by Ingalhalikar et al. (2014), in which $n = 949$ children and adolescents between the ages eight and 22 years were examined, sex-specific differences are attributed to different brain sub-networks and connectivity's. Nevertheless, it remains unclear what these results mean at the behavioral level. At the behavioral level, Brocki and Bohlin (2004) explain possible sex-specific results in EF by the fact that girls tend to be more cautious and conscientious, which is also supported by Weisberg et al. (2011).

Discussion of Methods

One of our central questions is whether elite athletes and amateurs differ in general cognitive abilities or in certain sport-specific cognitive abilities. In taking a closer look at the current state of research, two different approaches are applied. According to Voss et al. (2010), sports training is a form of cognitive training that leads to better neuronal connectivity and plasticity and thus to improved general cognitive performance ("Cognitive Component Skill Approach"). However, this approach neglects the complex environment (specific to sports games), which also seems important to support the superiority of experts. The "Expert Performance Approach" (Mann et al., 2007; Williams et al., 2017), on the other hand, is an approach in which cognitive performance is examined in an ecologically valid and sports-specific environment and is thus representative of the specific domain of an expert. In order to be able to show clear differences between elite athletes and amateurs, sport-specific tasks with cognitive requirements that are also needed during sport are probably more suitable. Thus, the specificity of the tasks seems to play an important role in expertise research. Based on our results, a shift in the field of expertise research is necessary, which does not exclusively consider Cool EF, but instead also uses Hot EF within the "Expert Performance Approach" and the "Cognitive Component Skill Approach."

In order to increase the above mentioned specificity of the tasks and to be able to observe the expertise effects more sensitively, one possibility is to think about how Cool EF tasks can be transformed into Hot EF tasks. One approach would be to select stimuli that trigger emotions. For example, faces are considered to be a special type of stimuli (Kanwisher et al., 1997) that very quickly convey emotions through different facial expressions. In addition to the appropriate selection of affective objects (e.g., faces) or situations (e.g., excessive harshness), the context in which information is received may vary depending on the relationship to persons, their personal history and other environmental conditions. Another possibility would be to generate frustration by giving false "right/wrong" feedback on the accuracy of the response. Thus, if a good performance in a reaction time experiment (e.g., flanker task) is expected from individuals, frustration may be caused by unexpected false negative feedback regarding this performance (e.g., Agnoli et al., 2019). For this transformation, however, the necessary and sufficient conditions must be defined for what qualifies a task as Hot or Cool. Assuming a continuum, each task individually has a more or less significant proportion of Hot EF requirements (Peterson and Welsh, 2014). It would be helpful to have clear criteria so that EF tasks are not randomly arranged along this Hot-Cool continuum. Due to the small number of studies dealing with this topic, there are currently no clear criteria for allocation within this continuum. In this respect, the central question remains which aspects of a task need to be manipulated to trigger certain processes (Hot or Cool processes). Without being able to answer this question conclusively, we propose a 4-Dimensional classification of experimental paradigms, in which we differentiate between tasks of different specificity (general vs. sport-specific), between Cool and Hot EF, and between task complexity (simple Cool EF: inhibition, working memory, shifting/flexibility; simple Hot EF: inhibitory control, attention control, attention shifting; complex EF: planning, problem-solving, error monitoring, updating, organizing, setting goals, creativity, cognitive regulation; complex Hot EF: delay of gratification, error monitoring, persistence, willpower, coping, resilience, emotion regulation). In addition to this three-dimensional division, we can distinguish between dominantly open (e.g., team soccer, team handball) or closed sports skills (e.g., athletics) (see **Figure 8**).

Such a task specificity classification makes it possible to better classify and generalize study results and to provide differentiated recommendations for training and research. It is quite conceivable that the studies with the general "Cognitive Component Skill Approach" may lead to inconsistent results, because the emotional component that arises from the respective

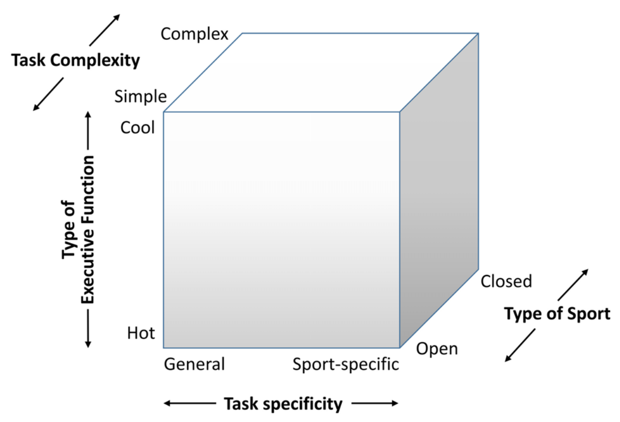

FIGURE 8 | Proposed four-dimensional classification multicomponent system to examine expertise effects in sport.

sport is missing. Presumably, the expertise effect becomes clearer when the spectrum shifts from sport-specific Cool to Hot functions. According to this argumentation, one would expect the most significant differences in the "Expert Performance Approach" with sport-specific complex Hot EF. Moreover, this is especially the case if one can clearly distinguish between the different levels of expertise.

In this context, the concept of expertise is another important aspect to be considered. Swann et al. (2015) created a classification system of sports expertise samples that distinguishes four types of elite competitive athletes. This classification allows an operational definition of expertise in a further continuum of "eliteness" in order to be able to classify the results of studies as transparently as possible. The authors thus make an initial proposal on how a valid expert sample can be selected for future research (p. 11). Central variables of this definition within a sports comparison (highest standard of performance, success at the athlete's highest level and experience at the athlete's highest level) are taken into account in our sample. The variables between the sports comparisons (Competitiveness of sport in athlete's country, global competitiveness of sport) are not taken into account since all athletes were recruited in Germany. Scharfen and Memmert (2019) also call for clarification of the terms "expert" and "elite." According to Ericsson et al. (1993), expertise is defined by the amount of deliberate practice. The "elite" athletes are categorized as those who compete at the highest level of competition in their respective sport, which makes it possible to differentiate between competition levels. The authors use the terms high-performance athletes and low-performance athletes, so this approach is consistent with the proposal of Swann et al. (2015), who consider both aspects (experience and competition level). Scharfen and Memmert (2019) noted that a differentiation based on experience might not be sufficient to distinguish between high-performance athletes and semi-professional athletes. For future research, they recommend assigning athletes to the high performance level via the elite instead of the expert definition (p. 848).

CONCLUSION

The aim of this study was to investigate possible differences in Hot and Cool EF between close- skills sports and open-skills sports, taking into account performance level and controlling for sex, training experience, and training duration. Although a significant overall effect for expertise in favor of elite athletes was observed, we did not identify main effects for type of sport or an interaction for expertise x type of sport for Cool and Hot EF. In conclusion, the results are not as clear cut as one might have been expected from previous studies. In particular with regard to methodological aspects, we see great potential to make progress in this field, which is why we proposed a 4-D classification of experimental paradigms.

As mentioned above, it is difficult to determine whether those athletes who perform better in their EF remain and establish themselves in sport, or whether better performance in their EF is due to sporting demands [nature vs. nurture problem; "which came first, the potential athlete with a particular profile of cognitive abilities, or the potential athlete that acquires a particular cognitive skill set as a result of experience-dependent learning and brain plasticity" (Voss et al., 2010, p. 823)]. It is about the source (e.g., genetic, frequencies and intensities of deliberate practice) of expertise. In this context, it is discussed whether better cognitive functions contribute to athletes becoming elite athletes or whether constant exposure in a cognitively demanding sports situation leads to better trained cognitive functions (Miyake and Friedman, 2012; Jacobson and Matthaeus, 2014; Verburgh et al., 2014; Elferink-Gemser et al., 2018). For this purpose and with regard to the performance of the EF, longitudinal studies are necessary to compare the degree of expertise. In addition, longitudinal studies could examine the influence of expertise and type of sport on the developmental trajectories of EF (both Cool and Hot) in adolescents. Previous studies of the developmental trajectories of Hot and Cool EF show that age-related improvements in Cool EF can be observed as early as childhood at the age of 8 to 13 years, while improvements in Hot EF tend to be gradual and occur later in adolescence, typically from around 14 years of age (Crone and van der Molen, 2004; Hooper et al., 2004; Prencipe et al., 2011; Poon, 2018). Poon (2018) also argues that while the Cool EF follows a linear developmental trend, the Hot EF follows a bell-shaped curve, leading to a susceptibility to risky decisions in mid-adolescence (14–15 years). Against this background, it seems necessary to use a variety of sports and comprehensive neuropsychological methods with Cool and Hot EF to cover a broad spectrum of cognitive abilities in order to investigate the relationship between expertise or sport and cognitive performance. In the recently published meta-analysis by Scharfen and Memmert (2019), the authors recommend using cognitive test methods for scouting and screening sports talents and thus optimizing their sporting development. The central question, however, is which tasks are suitable for this. Nyongesa et al. (2019) found in this context that a large number of different tasks and measures are used to assess EF in adolescents, but that the evidence of the psychometric robustness of these measures remains limited in order to prove the validity of their use in the elite context. In particular, psychometric properties are needed for the still few tasks that require Hot EF. In any case, we are convinced that Hot EFs can bring significant added value to the context of expertise research.

Furthermore, many studies mention the demand for a larger sample for higher statistical significance and more transferable statements (e.g., Huijgen et al., 2015; Elferink-Gemser et al., 2018). For future studies, it will be important to increase the statistical power of larger samples with a broad age range between childhood and young adulthood. Another central problem in expertise research is the access and willingness of competitive athletes to participate in such studies and especially in intervention studies. This would often mean taking athletes out of everyday training and, if necessary, intervening in training management. In addition, we didn't control for confounding variables such as fitness level or personality traits. On top of the advantageous experience-based development of the elite athletes with regard to cognitive performance

(Romer, 2010), possible confounders such as IQ, educational level/academic performance and socio-economic status must be taken into account (Wang et al., 2013b; Elferink-Gemser et al., 2018). This was mainly necessary in order to keep the testing effort manageable for the athletes. Furthermore, it must be clearly defined what is meant by elite. Swann et al. (2015) created a classification system of sports competence samples that distinguishes four types of elite performers. Last, but not least, we used only one task (Game of Dice Task; Brand et al., 2005) to examine Hot EF. As mentioned above, one idea is to manipulate Cool EF tasks (modified Flanker, N-back task, trail making/walking test) to transform them into tasks that increase the demand for Hot EF.

The application of experimental tasks originally developed for adults provided the opportunity to observe the development and change of cognitive functions during development (mainly Cool EF). This approach does not seem to be able to go beyond the temporary operational definitions of EF that they advocate (Miyake et al., 2000; Friedman and Miyake, 2017). Therefore, the EF construct requires further conceptual and empirical clarification, especially with regard to the exploration of emotional and motivational aspects (Hot EF). In particular, a renewed search is needed to help situate EF as a skill that is contextual and dynamically changing during development. We see EF as a consequence of the interaction between temperament and environment, and EF is strongly influenced by individual motivational drives. It seems certain that it is no longer possible to examine EF or its components from the perspective of a single methodological paradigm or from the perspective of a single theoretical position. Multidisciplinarity is crucial, which means that EF research in the next decade will almost certainly explore the dynamic relationship between brain function and structure, individual priorities, self-regulation, social context, individual information processing capacity, temperament and personal history (Müller and Kerns, 2015; Schott and Klotzbier, 2018). Such efforts are promising to demonstrate the scope of EF and the role it plays in human development, especially when it comes to the impact of expertise on cognition.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of Stuttgart. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

ME and BH performed the measurements. BH, TK, and NS were involved in planning, supervising the work, processing the experimental data, performing the analysis, drafting the manuscript, and designing the figures. All authors discussed and aided in interpreting the results and worked and commented on the manuscript.

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SUPPLEMENTARY MATERIAL

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BRIEF RESEARCH REPORT
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Running During Encoding Improves Word Learning for Children

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The learning of new information is an important task in everyday life, especially at a young age. Acute physical exercise can facilitate cognitive processes in multiple ways, and previous studies have shown that memory can profit from physical exercise before and during the encoding of vocabulary. The current study investigates the interplay of movement and vocabulary learning and also addresses lifespan differences in these effects. Participants were recruited in a recreational basketball club. Children (n = 24, M_{age} = 12.3 years; 13 girls), young adults (n = 30, M_{age} = 21.5 years; 17 women), and older adults (n = 24, M_{age} = 59.3 years; 9 women) learned 20 new pseudo-words, which corresponded to a German word. In a between-subjects design, encoding took place either while standing, while running, or while running and dribbling a basketball. Recall was assessed three times throughout the learning session and on the following day. In children, more words could be remembered in the running condition compared to the standing condition. There were no differences between conditions for the young and older adults. Age-dependent reasons for this pattern of results are discussed and embedded into the literature of physical exercise. Our result suggests that implementing learning activities into children's physical education or exercise activities could be beneficial.

Keywords: physical exercise, acute physical exercise, lifespan, word learning, vocabulary, memory

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INTRODUCTION

The learning of new information is an important task in everyday life. Physical exercise can improve cognitive performances, which has been demonstrated for long-term as well as acute exercise interventions. Chronic physical exercise has been shown to enhance cognitive processes in multiple ways [see a review by Tomporowski et al. (2008) and a meta-analysis by Verburgh et al. (2014)]. In addition, chronic physical activity can support physical and cognitive development in childhood (Hillman et al., 2011), as well as academic achievement (Alvarez-Bueno et al., 2017; Singh et al., 2018), and it may also reduce cognitive and motor decline in older adults (Bherer et al., 2013; Paillard, 2015; Roig et al., 2016).

Furthermore, a single bout of acute physical exercise can facilitate various cognitive functions, from executive functions like inhibition, verbal fluency, decision making, and stroop interference (Chang et al., 2012) to memory processes involving the encoding and consolidation of new information (Roig et al., 2013). Several reviews and meta-analyses (Etnier et al., 1997; Tomporowski, 2003; Chang et al., 2012; Roig et al., 2016; Loprinzi et al., 2019) have concluded that the overall effects are small, and are moderated by the duration, the intensity, the type, and the timing of the exercise.

Acute exercise increases one's heart rate, which can contribute to achieve an optimal level of neurological and physiological arousal, supporting the engagement in cognitively demanding tasks (McMorris and Graydon, 2000; Audiffren et al., 2008). Furthermore, there seems to be a link between physical exercise and the release of several neurobiological substrates that may enhance memory processes, like neurotrophins or certain neurotransmitters (Chmura et al., 1994; Davranche et al., 2006; Roig et al., 2013). In this context, Winter et al. (2007) assessed peripheral levels of catecholamines (dopamine, epinephrine, and norepinephrine) and brain-derived neurotrophic factor (BDNF) of young adults before and after high intensity running, low intensity running, or a period of rest. Directly after the intervention, after 1 week, and after 8 months, participants took part in an associative vocabulary learning task. After high intensity running, participants were 20% faster in learning the vocabulary and showed the strongest increases in BDNF and catecholamine levels. Higher levels of BDNF were related to better short-term learning, whereas higher levels of dopamine correlated with intermediate- and epinephrine with long-term retentions of the new vocabulary.

Overall, acute physical exercise affects the release of different neurobiological substrates, which may moderate memory encoding (Winter et al., 2007) and memory consolidation (Cahill and Alkire, 2003; Chowdhury et al., 2012). Due to the time-dependent nature of these two memory processes, memory encoding can be mainly effected by physical exercise before or during encoding, while memory consolidation would be more strongly affected by a bout of physical exercise after encoding (Roig et al., 2016).

The majority of studies investigating the acute effects of exercise on memory processes asked participants to exercise either before or after memory encoding (Schramke and Bauer, 1997; Coles and Tomporowski, 2008; Pesce et al., 2009; Labban and Etnier, 2011; Etnier et al., 2014; Hötting et al., 2016; for a recent review, see Loprinzi et al., 2019). However, there is also an increasing body of research showing that acute exercise *during* memory encoding can enhance episodic memory performance (Schmidt-Kassow et al., 2010, 2013, 2014; Mavilidi et al., 2016; Liu et al., 2017).

Mavilidi et al. (2017) used physical exercise to teach 90 preschool children the names and positions of planets of our solar system. Children were either sitting, running laps around the room (task-unrelated physical activity), or they were running successively from the sun to the planets lying on the floor (task-related physical activity) while the teacher repeated the names of the planets. Although children in the task-related physical activity group had the highest memory scores in an immediate and a delayed retention test, the task-unrelated group, which performed a typical acute exercise while encoding, also had significantly higher memory scores, compared with the control group.

The positive effect of physical exercise during memory encoding could also be shown for language learning tasks. Liu et al. (2017) tested 40 Chinese-English L2-learners in a vocabulary learning task. The learning phase included eight test sessions with one session per week. Each to-be-learned list was presented to the participants three times per session. The list consisted of 40 picture-name pairs. During learning, participants were either seated or were bicycling at 60% of their maximum heart rate. After each session and 1 month after the last session, participants took part in a word–picture verification task and in a semantic judgment task. Already after the first training session, the physical exercise group remembered more correct picture-name pairs in the picture verification task, while it took several weeks before they outperformed the control group in the semantic judgment task. This result indicates that already a single bout of physical exercise can have a positive effect on vocabulary learning.

In a similar way, Schmidt-Kassow et al. (2010) tested 12 adult native German speakers in three sessions per week for 3 weeks. During each session, the participants listened twice to the same 80 French-German word-pairs while being seated (control group) or while cycling (physical exercise group) at moderate speed. After every third learning session, participants' knowledge of the to-be-learned words was tested. The physical exercise group remembered more words compared to the control group. In a later study, Schmidt-Kassow et al. (2013) could replicate their results. They tested 105 German native speakers in a similar study design, except that this time there was an additional group that bicycled before memory encoding. Furthermore, participants learned a list of 80 Polish-German word-pairs, in only two learning sessions, and participants performed only two vocabulary learning tests. The results of the vocabulary learning tests revealed better memory performance for the group that cycled during encoding compared to the control group.

While the studies by Mavilidi et al. (2017) and Schmidt-Kassow et al. (2010, 2013, 2014) indicate that memory encoding in young children and in young adults can profit from concurrent exercise, findings for older adults appear less promising. To our knowledge, the effects of acute exercise *during* memory encoding in older adults have mainly been investigated in the context of cognitive-motor dual-task research. The general assumption in these study paradigms is that older adults have to invest more cognitive resources into seemingly automatized motor tasks like walking, and therefore show more pronounced performance decrements (dual-task costs) when a motor and a cognitive task have to be performed concurrently (for reviews, see Woollacott and Shumway-Cook, 2002; Schaefer, 2014). Studies by Lindenberger et al. (2000) and by Li et al. (2001) asked young and older adults to encode word lists (using a memory strategy) while walking on narrow tracks of different complexities. In these studies, older adults indeed showed pronounced performance reductions in memory when encoding took place while walking as opposed to sitting. However, the tracks used in these studies had been constructed to be rather challenging to walk on (narrow, sometimes with numerous turns, and sometimes including obstacles). It therefore remains unclear whether walking/jogging without such challenges has beneficial effects on memory in older adults.

Findings on acute exercise effects before or after a memory task in older adults are equivocal. Stones and Dawe (1993) asked elderly nursing home residents to perform a word fluency task (memory retrieval) before or after performing a 15-min non-strenuous exercise (intervention group), or after watching a video. Participants in the exercise group retrieved more category exemplars following exercise than the control group. In addition, Segal et al. (2012) reported post-learning exercise to enhance memory consolidation in older adults with and without mild cognitive impairment. However, Schramke and Bauer (1997) did not find improvements in the learning of word lists following exercise in young and older adults compared to a resting condition.

The current study investigates lifespan differences in the acute effects of exercise on vocabulary learning. We tested children, young adults, and older adults in a vocabulary learning task. Subjects were recruited via a local basketball club, and were all experienced basketball players. The participants learned pairs of words and pseudo-words, either while standing, while running, or while running and dribbling a basketball. Based on previous reports of enhanced vocabulary learning while exercising (Schmidt-Kassow et al., 2010, 2013, 2014), the positive influence of acute physical exercise on establishing an optimal physiological arousal (McMorris and Graydon, 2000; Audiffren et al., 2008), and the link between exercise and the release of neurobiological substrates that enhance memory processes (Chmura et al., 1994; Davranche et al., 2006; Roig et al., 2013), we hypothesized that more words are remembered when encoding takes place while running as compared to standing in all age groups. Furthermore, we assume that running while dribbling a basketball (as compared to running only) exerts an additional cognitive load. The cognitive load theory (see Sweller et al., 1998, 2019) distinguishes three types of cognitive load. *Intrinsic cognitive load* refers to the complexity of the information being processed, while considering the knowledge of the person processing the information. *Extraneous cognitive load* includes the instructional procedures that may reduce or increase cognitive load. *Germane cognitive load* describes the resources available to deal with intrinsic cognitive load (Sweller et al., 2019). In this context, dribbling a basketball is expected to increase the extraneous cognitive load, since it is a complex motor skill requiring attentional resources. However, motor expertise is influenced by experience and age: Younger adults should be able to compensate for the additional task with their experience in basketball dribbling, having reached a stage of complete automation of the motor task (Fitts and Posner, 1967). Children, on the other hand, still have to devote some attentional resources into the dribbling task, and may have fewer resources overall. And older adults have to compensate for aging-related declines in sensory and motor systems, as assumed by the dual-task literature (Kahneman, 1973; Navon and Gopher, 1979; Schaefer, 2014). We therefore predict that running while dribbling a basketball reduces the number of words remembered in children and older adults, but not in young adults. Lastly, we assume that all age groups will improve from recall 1 to recall 3, which reflects the learning process.

METHODS

Participants

A statistical *a priori* power analysis was performed for sample size estimation (GPower 3.1.9.2). According to the current literature (Schmidt-Kassow et al., 2013, 2014), we assumed a large effect size (f = 0.40) with an α = 0.05 and power = 0.80 for the estimated main effect of condition, which resulted in a suggested sample size of N = 66. Twenty-four children (M_{age} = 12.3 years; 13 girls), 30 young adults (M_{age} = 21.5 years; 17 women), and 24 older adults (M_{age} = 59.3 years; 9 women) were recruited and tested in a recreational Basketball club at the Saarland. All of them had normal or corrected-to-normal vision and hearing. The declaration of consent was signed by all participants, in case of children by their legal guardian. The study was approved by the Ethics committee of Saarland University. The current study has been preregistered under the following link: https://aspredicted.org/blind.php?x=3qf4yt.

Cognitive Background Variables

To allow for comparisons across the three age groups, tests for cognitive speed (Digit Symbol Substitution task, Wechsler, 1981), sustained attention (D2 Test, Brickenkamp et al., 2010), and knowledge of German vocabulary (MWT-A questionnaire, Lehrl et al., 1991) were measured and used as background variables. Consistent with the developmental literature (Li et al., 2004), young adults outperformed children in cognitive speed, while older adults showed the highest scores in the test for knowledge of German words (see **Table 1** for descriptives and cognitive background information).

Experimental Task

Vocabulary Learning Task

The Vocabulary Learning task was constructed based on extensive piloting of the paradigm. Measures of retest reliability are depicted in **Table 1**. The goal of the task was to learn a list of 20 new pseudo-words. Each pseudo-word corresponded to a German word. Pseudo-words were constructed using syllables that can be pronounced in the German language (examples of pseudo words: kebruli, curlef, and ogizav). A word-pair was presented for 6 s on a large screen (for example, Wolf – kebruli) to make sure that participants of each age group had enough time to read the word-pair. Then participants had 7 s to encode the word-pair, without seeing it any more on the screen. We argue that this time interval has to be used for active encoding processes (i.e., continuous rehearsal), since participants had to enter both words using a computer keyboard immediately afterward. Immediate recall accuracies were very high in all age groups (see **Table 1**). After 15 s, which was enough time to enter the word-pair and to refocus on the screen, the next word-pair was presented, until all word-pairs of the list had been presented. A sound signal indicated when the 6 s presentation time, the 7 s encoding time, and the 15 s enter time ended.

In a between-subjects design, the 7 s of encoding took place either while standing, while running, or while running and

TABLE 1 | Descriptives, cognitive background information, and reliability of the vocabulary learning task.

Group	Children (C)	Young adults (YA)	Older adults (OA)	ANOVA*
n Age (years)	24 (*f* = 13) *M* = 12.3 SD = 1.3	30 (*f* = 17) *M* = 21.5 SD = 4.4	24 (*f* = 9) *M* = 59.3 SD = 5.1	
Basketball experience (years) Training per week (number of sessions) Still playing actively (percentage)	*M* = 4.2 SD = 1.9 *M* = 3.3 SD = 1.3 100%	*M* = 11.8 SD = 5.3 *M* = 3.5 SD = 1.2 100%	*M* = 40.5 SD = 5.4 *M* = 1.1 SD = 0.2 46%	OA > YA > C, $F(2,50) = 244.20$, $p < 0.001$ YA = C > OA, $F(2,54) = 18.71$, $p < 0.001$
Digit symbol substitution (cognitive speed; items per second)	*M* = 0.5 SD = 0.1	*M* = 0.7 SD = 0.2	*M* = 0.5 SD = 0.1	YA > C = OA, $F(2,75) = 16.71$, $p < 0.001$
D2 (sustained attention, score)	*M* = 114.0 SD = 29.7	*M* = 120.4 SD = 19.4	*M* = 136.3 SD = 42.8	OA = YA > C, $F(2,75) = 3.25$, $p < 0.05$
MWT-A (vocabulary, number of correct solutions)	*M* = 21.4 SD = 4.0	*M* = 28.2 SD = 3.2	*M* = 31.9 SD = 1.7	OA > YA > C, $F(2,75) = 68.15$, $p < 0.001$
Immediate recall accuracy [%] German word (GW) Pseudo word (PW)	 93.19 87.71	 97.61 92.00	 94.72 85.28	GW > PW, $F(1,75) = 56.54$, $p < 0.001$ No sign. main effect of age group, $F(2,75) = 2.72$, $p = 0.073$, or age group × language interaction, $F(2,75) = 1.97$, $p = 0.147$
Retest reliability for recall time 1 to recall 3 (Cronbach's Alpha)	α = 0.882	α = 0.946	α = 0.885	

**Significant effects have been further analyzed with independent-samples t-tests.*

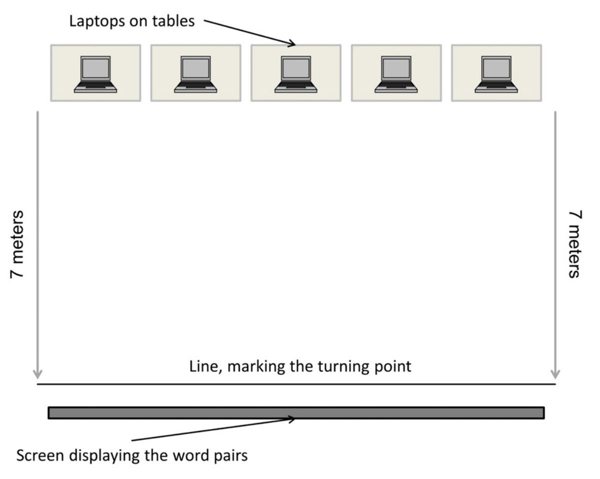

FIGURE 1 | Experimental setup of the vocabulary learning task.

dribbling a basketball. The distance in both running conditions was 7 m forth and 7 m back to where the Laptops stood (see **Figure 1** for the experimental setup). The distance of 14 m was chosen to induce a moderate running speed, which was adapted to the encoding time of 7 s.

Following the 20 word pairs of each list, participants took part in a cued recall test, where only the German words were presented and the participants had to enter the corresponding pseudo-words. During recall, German cue words were presented one at a time in randomized order. Participants had no time limit to answer the cued recall test. Two additional encoding and recall trials were administered in the testing session, using the same word-pseudo-word pairs, but always in randomized order, resulting in three repetitions of the to-be-learned lists.

On the following day, each participant received an email with a link to a fourth cued recall test via internet. The dependent variable for memory was the number of correctly spelled pseudo-words in each cued recall test. Spelling errors were not scored as a remembered word.

Procedure

Before data collection started, each participant's identification number was randomly assigned to one of the three treatment conditions (standing, running, and dribbling) using a random algorithm of the program Microsoft Excel. Participants were tested in groups with up to five participants completing the same condition. The test session lasted for about 1 h and started with the completion of the demographic questionnaire, that included questions about age, sex, and sport activities. Then each participant was assigned to one of the five laptops standing on the tables. The test administrator explained the task and how the words had to be entered in the laptop. Then participants took part in a practice phase with one word-pair until everyone got used to the timing of the encoding phase. For participants in the running and dribbling conditions, the practice phase was also used to accustom participants to the required running speed. We did not observe any dribbling mistakes throughout the entire study. After practice, the first 20 word-pairs were presented. Following every cued recall test, participants completed one of the three background tasks (after trial one: Digit Symbol Substitution; after trial two: MWT-A; after trial three: D2). Working on the cognitive tasks between the trials led to a schedule of distributed rather than massed practice for the memory-encoding task within a testing session. On the following day, participants were reminded via text messages to fill in the cued recall test one more time (internet based assessment).

Data Analysis

The vocabulary learning task was analyzed with a mixed-design analyses of variance (ANOVA) with position (recall 1–4) as within-subjects factor and age group (3: children, young adults, and older adults) and condition (3: standing, running, and running and dribbling) as between-subjects factors. *F* values and partial Eta square values for effect sizes are reported. If sphericity assumptions were violated, Greenhouse–Geisser corrected values are reported. The alpha level used to interpret statistical significance was $p < 0.05$. Significant main effects were further investigated by planned *t*-tests with Bonferroni corrected levels of significance. If the *a priori* Levene-Test was violated, values for *t*-tests with unequal variances are reported. For paired-samples *t*-tests, we present Cohen's d_z effect sizes and for independent samples *t*-tests, we present Cohen's *d* effect sizes (Cohen, 1988).

RESULTS

Vocabulary Learning Task

The ANOVA with position (4) as within-subjects factor and age group (3: children, young adults, and older adults) and condition (3: standing, running, and running and dribbling) as between-subjects factors was conducted to investigate the effects of acute physical exercise on vocabulary learning. **Figure 2** depicts the pattern of findings.

The results of the ANOVA show a significant main effect of position, $F(1.58,109.19) = 109.820$, $p < 0.001$, $\eta^2p = 0.614$. Paired-samples *t*-tests (Bonferroni corrected level of significance to $p < 0.008$) indicate significant performance increases during the learning session from recall 1 to recall 3, followed by a performance reduction comparing recall 3 with recall 4 (see **Table 2**). There was a significant main effect of age group, $F(2,69) = 16.588$, $p < 0.001$, $\eta^2p = 0.325$. Independent samples *t*-tests indicate that children ($M = 3.14$, SD = 2.67) remembered more words than older adults ($M = 1.52$, SD = 1.51), $t(46) = 2.583$, $p < 0.02$, $d = 0.75$, but fewer words than younger adults ($M = 5.82$, SD = 3.67), $t(52) = 3.105$, $p < 0.01$, $d = 0.82$. Young adults remembered more words than older adults, $t(52) = 5.825$, $p < 0.001$, $d = 1.47$. The results showed no main effect of condition, $F(2,69) = 0.59$, $p = 0.560$, $\eta^2p = 0.017$. Furthermore, the results show a significant interaction of position and age group, $F(3.17,109.19) = 13.771$, $p < 0.001$, $\eta^2p = 0.285$. This interaction can be explained by paired-samples *t*-tests (Bonferroni corrected level of significance to $p < 0.008$) showing that children's and older adult's memory performance decreases from recall 3 to recall 4, but young adult's performance does not. In addition, children's and older adult's performance does not significantly differ between recall 2 and recall 4, whereas young adult's performance does improve. The results show no interaction of position and condition, $F(3.17,109.19) = 0.885$, $p = 0.456$, $\eta^2p = 0.025$, and no interaction of condition and age group, $F(4,69) = 2.173$, $p = 0.081$, $\eta^2p = 0.112$, but we see a significant three-way interaction of position, age group, and condition, $F(6.33,109.19) = 2.302$, $p < 0.05$, $\eta^2p = 0.118$. Paired-samples *t*-tests show that children remembered more words in the running condition compared to the standing condition at recall 2, $t(14) = 2.646$, $p < 0.02$, $d = 1.32$, recall 3, $t(9.97) = 3.157$, $p < 0.02$, $d = 1.58$, and recall 4, $t(9.15) = 2.54$, $p < 0.04$, $d = 1.27$. Comparing the dribbling condition and the standing condition, they only remembered more words at recall 2, $t(14) = 2.229$, $p < 0.05$, $d = 1.12$ (see **Figure 2A**). For the young adults, there was only one difference between the running and dribbling condition at recall test 1, $t(9) = 2.33$, $p < 0.05$, $d = 1.04$ (see **Figure 2B**), and there were no differences between conditions for the older adults at any recall test (see **Figure 2C**).

DISCUSSION

The current study aimed to investigate if physical exercise during vocabulary learning can enhance memory performance

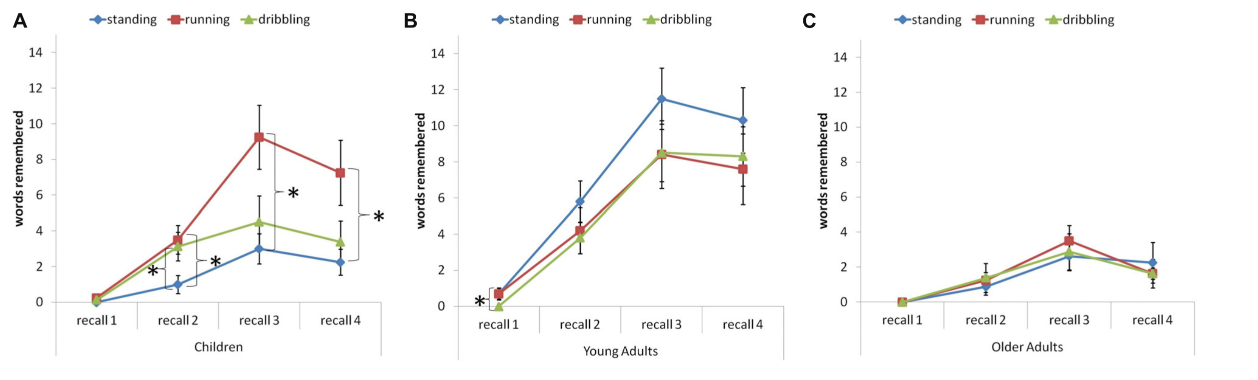

FIGURE 2 | Memory performance in the vocabulary learning task of children **(A)**, young adults **(B)**, and older adults **(C)** at recall test 1 to 4, in the standing, running, and dribbling conditions. Asterisks indicate results with $p < 0.05$. Error bars = SE means.

TABLE 2 | Follow-up analysis of the significant main effect of position with paired-samples *t*-tests.

Comparisons	Difference of the means	*SD*	*t*	*p*
Recall 1 with rec. 2	−2.67	2.63	−8.949	<0.001
Recall 1 with rec. 3	−6.04	4.89	−10.913	<0.001
Recall 1 with rec. 4	−5.00	4.90	−9.004	<0.001
Recall 2 with rec. 3	−3.37	3.05	−9.778	<0.001
Recall 2 with rec. 4	−2.33	3.09	−6.678	<0.001
Recall 3 with rec. 4	1.04	1.83	−5.021	<0.001

of children, young adults, and older adults. We hypothesized that memory performance would profit from the running condition in all age groups. This hypothesis could be partially confirmed. Only children's memory performance benefited from running during memory encoding, whereas young and older adults' performances were comparable for standing and running conditions.

But why did only children profit from physical exercise, and not young or older adults? In the current study, all age groups ran at the same speed in order to keep the running distance and the encoding time comparable between the age groups. It is possible that younger adults did not benefit to the same extent as children since children may have experienced a higher physical exertion at the same running speed. Exercise-induced changes in arousal and neurobiological substrates may have been too low in the young adult group, and a higher intensity (faster running speed) could have changed the pattern of results (Chang et al., 2012). However, recent studies have shown that even walking at a preferred speed can facilitate memory performance (Schmidt-Kassow et al., 2014).

Another explanation could be that running has interfered with the use of cognitive strategies, like rehearsal (actively repeating information), deep encoding (linking the information with associations or images), or clustering (organizing new information into related groups). In reference to the cognitive load theory (Sweller et al., 2019), younger adults should have a larger knowledge base to connect the to-be-learned words with in their long-term memory. They can then use their working memory to embed the new words into pre-existing semantic structures via deep encoding, and such processes may work best when not being distracted by physical activities. In fact, it seems as if young adults were most successful in memory encoding while standing, even if this trend does not reach significance in the current study. Compared to adults, children do not consistently use cognitive strategies yet (Ornstein, 1978; Schneider, 2008). Instead, the structure and rhythm imposed by the running condition may have helped them to engage in memory strategies like continuous rehearsal. In future research, the use of cognitive strategies should be taken into account, for example by instructing participants to use a specific strategy like the method-of-loci, which integrates the new information into visualizations of familiar places (Li et al., 2001). A thorough monitoring of exercise intensity and physical exertion using heartrates or physical exertion questionnaires would help to interpret future findings.

For older adults, we did not find any differences between the three conditions. Overall, the memory performance of this age group was very poor. On average they only remembered three words (SD = 2.50) out of 20 possible words at their best recall test (recall test 3). These results indicate that the task-difficulty of the memory task was too high for older adults, making it difficult to interpret the current results. Dual task studies using walking and memory encoding in older adults would even have predicted memory performance decrements (Lindenberger et al., 2000; Krampe et al., 2011; Schaefer et al., 2014), but these studies used rather challenging walking conditions like virtual worlds, narrow tracks, or obstacles. Future studies on memory encoding while exercising should try to avoid floor or ceiling effects in the motor or memory task. It could be worthwhile to adjust task-difficulties individually, or at least on the level of age groups.

Based on the motor learning and expertise literature (Fitts and Posner, 1967; Schaefer, 2014), we expected children's and older adults' memory performance to decrease in the dribbling condition, compared to the running condition, while young adults should be able to keep their memory performance stable. Our expectations could partially be confirmed. As expected, the results show no decrease in memory performance in the young adult group. However, contrary to our expectations, older adults also did not show memory performance decrements while dribbling. Again, this may be due to the excessive demands that older adults have been confronted with. Children showed comparable performance levels for standing and dribbling at the later stages of the study. Since all of our participants were experienced basketball players, running and dribbling a basketball may have been automatized even in our youngest participants already. Not all of the elderly participants were still playing basketball regularly. This lack of current practice of a motor skill could lead to de-automatization processes, making it more difficult to profit from certain types of exercise while learning. Future research should investigate motor expertise more systematically. Since a lack of power might have been responsible for not finding clearer effects in our study, future research should also test larger sample sizes and consider using within-subjects designs.

Another issue that is worth investigating is the exact timing of exercise and memory encoding. Beneficial effects of exercise on memory could be even larger if the exercise bout takes place before or after memory encoding (Chang et al., 2012; Roig et al., 2013; Loprinzi et al., 2019). Roig et al. (2016) argued that memory encoding may be more strongly affected by exercise before encoding, while memory consolidation may more affected by exercise after memory encoding. On the other hand, it may be possible that physical exercise during encoding is particularly appropriate for enhancing both memory processes, by optimizing arousal level throughout the entire learning phase.

The current study provides an example of how physical exercise could be implemented in other learning activities (e.g., vocabulary learning) (see Diamond and Ling, 2016, 2018; Hillman et al., 2018 for an ongoing discussion on physical activity and its effects on executive functions). The results of the current study show that the integration of physical exercise into memory encoding can be particularly beneficial for children. Using physical exercise that is meaningfully related to the cognitive task may lead to stronger effects (see Mavilidi et al., 2016, 2017). We conclude that the combination of physical and mental activities has power to improve learning while at the same time giving students the opportunity to be physically active. Schools should provide optimal learning environments and support students in acquiring efficient learning strategies. Physical exercise may contribute to achieve this goal by enhancing cognitive activation (Pesce et al., 2009) and thus facilitating the learning process stimulated by the school.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of Saarland University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

Both authors contributed to the study design and cooperated in conducting the literature review. GA analyzed and interpreted the data, with input from SS and led the drafting of the manuscript, with substantial contributions from SS.

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Deliberate Soccer Practice Modulates Attentional Functioning in Children

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The main purpose of this study was to explore the association between the regular practice of open-skill sports (i.e., soccer) and executive control, along with other attentional functions (i.e., alerting and orienting) during preadolescence. The study was conducted on 131 participants (70 non-athletes and 61 soccer players). To measure cognitive performance, participants performed the Attentional Network Test—Interactions (ANT-I) task. Compared to non-athletes, soccer players showed overall faster responses and better executive control (e.g., reduced interference from distractors). Overall, our results provide new empirical evidence supporting the positive association between regular sports practice and cognitive performance, and more specifically executive functions. However, is important to note that the relationship between regular sport practice and cognition is complex and multifactorial. Our findings can be partly explained by the "cardiovascular fitness hypothesis" and the "cognitive component skills approach," suggesting that an externally paced sport environment with high physical fitness and perceptual–cognitive demands may be an appropriate setting to optimize the development of cognitive functioning during early adolescence.

Keywords: executive control, orienting, alerting, childhood, team sport

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INTRODUCTION

The physical, psychological, and socio-affective benefits of physical activity have been widely described in numerous scientific studies (see reviews by Eime et al., 2013; Warburton and Bredin, 2017; Milanović et al., 2019). Regarding benefits at the cognitive level, many studies have explored this association in older adults (see the review by Northey et al., 2018). In addition, a great deal of research has recently been conducted on children and young adults, revealing the positive influence of regular physical exercise on cognitive performance (see reviews by Donnelly et al., 2016; Bidzan-Bluma and Lipowska, 2018; de Greeff et al., 2018). However, not all physical activities (i.e., working, free play, and deliberate practice) are the same. Ericsson et al. (1993) defined the term "deliberate practice" in terms of the quality of the practice time, only considering as deliberate practice highly structured activities that have been specially designed to develop specific goals and, consequently, to improve the current level of performance. In our investigation, we will focus our interest on the study of the association between deliberate soccer practice and attentional functioning in children.

Among the various cognitive functions that have been studied, researchers have particularly focused on understanding the relationship between regular exercise and executive control, especially in older adults (see the review by Sanders et al., 2019) and other age groups (see reviews by Best, 2010, with children, and Guiney and Machado, 2013, with other age groups).

Executive control is defined as a set of high-level cognitive functions involved in the planning, initiation, sequencing, and analysis of complex, goal-driven behaviors (Diamond, 2013). These cognitive functions are grouped into three types of sub-processes: (a) inhibitory control, which involves the ability to filter out irrelevant information to avoid unnecessary responses and selectively maintain attention and control over one's actions; (b) working memory, which reflects the ability to keep in mind and manage information while performing complex cognitive tasks; and (c) cognitive flexibility, that is, the ability to restructure information and knowledge to efficiently adapt to various situational demands. In the sports context, executive control allows athletes to make quick decisions when faced with high cognitive demands. It also enables them to optimize their performance and is essential for their success, especially in externally paced sports with rich and complex stimuli (Vestberg et al., 2017).

The relationship between regular physical activity and executive control has been studied from different methodological approaches. The dominant approach has been to analyze cognitive performance using tasks that measure executive functions in laboratory contexts (e.g., Belsky et al., 2015; Chekroud et al., 2018). However, few studies have explored the association between regular practice of a specific sport and executive control, while simultaneously taking into account other attentional functions such as those described by Posner (1980): alerting, orienting, and executive control. Sports in general, and more specifically externally paced ones, are a rich environment to test this global function of attention given the complexity of the present stimuli and the decision-making processes involved. Therefore, our research focused precisely on analyzing the association between regular practice of a predominantly externally paced or open-skill sport such as soccer and executive control in the context of other attentional networks.

Regarding the positive link between regular physical exercise and executive control in children (see reviews by Guiney and Machado, 2013; de Greeff et al., 2018), most studies have focused on exploring the mediating effect of cardiovascular fitness (Buck et al., 2008; Hillman et al., 2009; Chaddock et al., 2010, 2012; Castelli et al., 2011; Davis et al., 2011; Pontifex et al., 2011; Voss et al., 2011). Overall, a positive correlation has been observed between the level of cardiovascular capacity and the performance of executive functions. These findings are based on the "cardiovascular fitness hypothesis" (North et al., 1990; Voss et al., 2011), according to which improved aerobic abilities, which are inherent to regular physical exercise, are the physiological mediator that determines cognitive benefits. More specifically, Hillman et al. (2009) and Pontifex et al. (2011) used various types of flanker tasks. They observed that preadolescent children with lower aerobic fitness showed less accuracy than those with higher fitness levels, although their speed of response was not affected. By contrast, studies such as that of Kimball (2009) have found no difference in antisaccade or flanker tasks between participants with regular aerobic practice and control participants with no regular practice. On the other hand, many studies have analyzed the relationship between sport expertise and executive control in young people, showing benefits in participants with greater skills in sports such as fencing (Chan et al., 2011), basketball (Alarcón et al., 2017), or badminton (Yu et al., 2017). These findings have been explained on the basis of the "cognitive component skills approach," according to which sports training acts as a means to improve brain plasticity and develop certain cognitive functions more efficiently (Voss et al., 2010; Scharfen and Memmert, 2019a). This would explain the "specialization" in attentional performance achieved by practicing predominantly open-skill sports. Focusing on studies carried out on children, Verburgh et al. (2014) observed that highly skilled soccer players showed greater motor inhibition than amateur soccer players but no differences in executive attention or visuospatial working memory. In a later study, these authors compared the sport practice level of three groups of children (i.e., highly skilled soccer players with very frequent practice, amateur players with regular practice, and non-athletes with no practice) on motor inhibition, short-term memory, working memory, and the three attentional networks: alerting, orienting, and executive attention (Verburgh et al., 2016). Their findings showed that the higher the levels of sports practice, the better the measured motor inhibition and short-term memory. Moreover, amateur soccer players outperformed non-athletes in both short-term memory and working memory. More recently, Scharfen and Memmert (2019b) reported a positive relationship between performance in basic cognitive skills (i.e., working memory, perceptual load, multiple object tracking, and attention window) and specific motor abilities (i.e., sprint, change of direction, dribbling, ball control, shooting, and juggling) in a small sample of elite youth soccer players ($n = 15$, $M_{age} = 12.72$).

Scarce evidence exist on the link between regular physical exercise and exogenous spatial orienting, yielding variable results (Nougier et al., 1996; McAuliffe, 2004; Verburgh et al., 2014). Nougier et al. (1996) found that young adults who practiced predominantly open-skill sports showed greater flexibility and attentional control than their counterparts who practiced predominantly closed-skills sports. In the same age group, using a spatial cueing task, McAuliffe (2004) found that cueing effects were greater in university volleyball players than in non-athletes. At younger ages, only the study by Verburgh et al. (2014), comparing a sample of highly skilled vs amateur soccer players (8–12 years old), reported no differences between groups in attentional orienting. The study by Buck (2008) also failed to find a relationship between aerobic physical fitness and orienting in a sample of preadolescent athletes.

Finally, the few studies conducted to date on the relationship between regular physical exercise and phasic alerting in children have yielded scarce and inconclusive results. Buck (2008) found no effect of increased aerobic fitness on the alerting network in preadolescent athletes. However, a study by Verburgh et al. (2014) showed that highly skilled soccer players responded faster to a warning signal than amateur soccer players. Other studies have shown a positive relationship between deliberate practice of sports with high perceptual and decision-making demands and tonic alertness or vigilance (Ballester et al., 2015, 2018, 2019).

As described in the above review, the association between regular exercise and attentional functioning in general, and executive control in particular, has generally been approached by analyzing each cognitive function in isolation. These studies have been mainly focused on samples of older adults (e.g., Colcombe and Kramer, 2003; Bixby et al., 2007; Prakash et al., 2011) and, to a lesser extent, on younger adults (e.g., Stroth et al., 2009; Kamijo and Takeda, 2010) and children (Chaddock et al., 2011a,b; Davis et al., 2011). In addition, most studies mentioned above have highlighted the mediating role of cardiovascular or aerobic fitness when explaining the beneficial effect of regular exercise on executive attention (e.g., Guiney and Machado, 2013).

The main novelty in our study resides is the exploration of the link between deliberate practice of a predominantly open-skill sport (soccer) and executive control in interaction with other attentional networks in children. Our research is based on previous findings, which generally showed some benefits of regular physical exercise on various functions linked to executive control. Accordingly, we expect to find better executive control in a group of children with deliberate soccer practice compared to a group of children with no practice.

MATERIALS AND METHODS

Participants

We conducted a cross-sectional study on a sample of 131 male children aged 10–12 years [M_{age} = 10.87 years old, standard deviation (SD) = 0.85]. Seventy of them were non-athlete primary school students (M_{age} = 10.84 years old, SD = 0.84) who fulfilled our previously defined inclusion criteria: no systematic sport practice or less than 5 h per week of sport participation outside school. These criteria were established according to data obtained from a survey on physical activity and sport practice habits. In order to guarantee systematization of practice and homogeneity of training, sleeping, and study habits, the athlete group, 61 children (M_{age} = 10.90 years old, SD = 0.86), were recruited from several U10 and U12 teams enrolled in a youth elite soccer academy of La Liga club in the Valencia region of Spain.

All participants self-reported normal or corrected-to-normal vision. Statistical analyses were conducted on data from only 113 participants, after excluding those who did not perform the task appropriately (a higher than 25% error rate—4 participants) and 4 non-athletes who practiced sport for more than 5 h per week.

A sensitivity analysis conducted with G* Power (Faul et al., 2007) showed that with our sample size divided into two groups (i.e., soccer players, 59, vs non-athletes, 54), the minimum effect size that could be detected for the between-group differences regarding each attentional function for $\alpha = 0.05$ and $1 - \beta = 0.80$ was $f = 0.188$ (i.e., minimum detectable effect).

The Research Institute of Sport Sciences of the Catholic University of Valencia granted ethical approval for this study (code UCV/2015/2016/22), which also complied fully with the 1964 Declaration of Helsinki and its later amendments. Participation in the study was voluntary; all participants and their parents or legal guardians were properly informed about the risks and benefits of the study prior to any data collection and signed an institutionally approved informed consent form. The participants were also informed of their right to leave the experiment at any time.

Procedure

All the tests were performed in a single experimental session lasting approximately 45 min in the afternoon during normal school hours or during the training hours of the soccer players. First, the group of non-athletes completed the questionnaire on their physical-sports activity practice habits, in which they had to specify whether they practiced any sports outside their school physical education classes, which sport or sports they practiced, if any, and the number of hours they performed this activity per week. This questionnaire was not completed by the group of soccer players because they all had three training sessions a week lasting approximately 90 min, in addition to a weekend match lasting approximately 90 min. Participants were given an explanation of the ANT-I (Attentional Network Test–Interactions) task developed by Callejas et al. (2004) and were then asked to complete it.

Cognitive Task

The ANT-I is a modified version of the Attentional Network Task, known as ANT (Fan et al., 2002). It was developed to assess the independent functioning of the three attentional networks (alerting, orienting, and executive control or inhibitory control), as well as the potential interactions between them; it combines a spatial orienting task (Posner, 1980), a flanker task (Eriksen and Eriksen, 1974), and an audio signal to assess the functioning of the phasic alerting network. The efficiency of each network and its interactions are measured by registering reaction times (RTs) and response accuracy (i.e., percentage of errors). Considering the complex relationships that underlie the perceptual contexts that characterize most team sports (for a review of the benefits of using the ANT-I vs the ANT, see Ishigami and Klein, 2010), the ANT-I seems a suitable task to measure attentional functioning.

Data collection took place in specially equipped data collection rooms, under dimly lit conditions with no distracting noises. Participants were seated approximately 60 cm from a 15-inch monitor in which the attentional task stimuli were presented using E-Prime software (Schneider et al., 2002). Participants wore headphones through which they could hear the acoustic warning signal. The experiment began by displaying instructions to perform the task, while the researcher in charge of the experiment provided any necessary additional information.

Participants were encouraged to respond as quickly and accurately as possible by pressing the "C" (left) or "M" (right) key on the keyboard depending on the direction of the target stimulus (a central target arrow 0.55° long pointing either left or right), which was flanked by two other irrelevant arrows identical to the target on each side (0.06° away from each other). In each trial, the target arrow was preceded by an acoustic alerting tone (2,000 Hz and 50 ms) and/or a spatial orienting visual cue (an asterisk 0.6° in size and 50 ms). Participants were strongly encouraged to fixate the fixation point (variable duration of 400–1,600 ms) throughout the entire trial. The sequence of events for each trial is shown in **Figure 1**. The interference variable

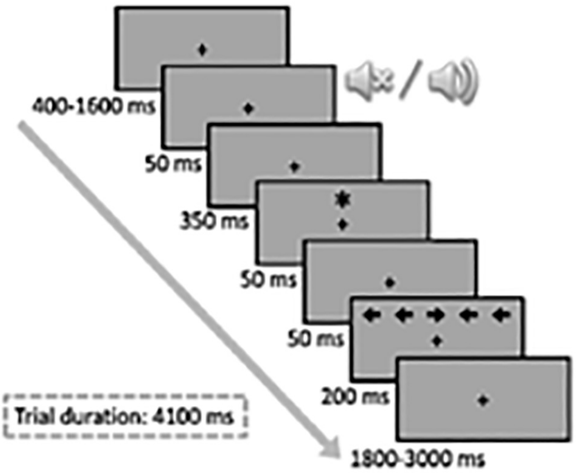

FIGURE 1 | Experimental procedure and stimuli sequence in the Attentional Network Test—Interactions task.

was defined according to the congruency of the direction of the flankers and target arrows: congruent trials (50% of trials), in which the target was flanked by arrows pointing in the same direction, and incongruent trials (the remaining 50% of trials), in which the flanking arrows and the target pointed in opposite directions. The orienting signal was presented above or below the fixation point in two-thirds of the trials. Three orienting conditions were thus established according to the presence of the cue: cued location trials, when the cue was presented at the same location as the target; uncued location trials, when the cue was presented at the opposite location to the target; and absence of cue, or no cue trials, when no cue was presented. The alerting signal was presented before the onset of the target in only half of the trials. The alerting variable was established according to the presence (tone) or absence (no tone) of the acoustic warning signal. The target was presented until the participants responded or for 1,700 ms. After the response, or after the allocated time had elapsed, the fixation point was presented for a variable length of time (depending on RTs and the duration of the initial display for that trial) so that all trials were equally long (4,450 ms). Initially, participants completed a practice block of two trials (including feedback about the response), followed by six experimental blocks of 48 trials each (without feedback), with resting intervals of about 1 min between them. Participants performed the ANT-I for approximately 25 min.

Statistical Analyses

Descriptive statistics (mean ± SD) were used to collect data on various aspects of the sample and groups. Normal distribution of data and the assumptions of sphericity were examined using Shapiro–Wilk and Mauchly tests, respectively. We conducted a mixed repeated-measures MANOVA on the data of each dependent variable (RTs and accuracy), with Deliberate Sport Practice (soccer players vs non-athletes) as a between-group factor and the other independent variables (Alerting: tone, no tone; Orienting: uncued, no cue, cued; and Congruency: congruent, incongruent) as within-participant factors. A first analysis was conducted by means of repeated-measures ANOVAs on both mean RTs and error percentages, including Alerting signal (no tone/tone), Orienting visual cue (invalid/no cue/valid), and Congruency (congruent/incongruent), in order to establish whether the usual pattern of results was observed. *Post hoc* analyses (paired *t*-tests) were conducted to further explore significant interactions, with the Tukey correction for multiple comparisons. The alpha level was set at $p < 0.05$ for univariate ANOVAs and repeated-measures ANOVAs. The partial eta squared (η_p^2) effect size was also reported, indicating small ($\eta_p^2 > 0.01$), moderate ($\eta_p^2 > 0.06$), or strong ($\eta_p^2 > 0.14$) effects (Field, 2009).

RESULTS

Descriptive Analysis of the Attentional Variables

Data from incorrect response trials (2.68%), or those whose RTs were 2.5 SD above (2.63% lapses) or below (0.05% anticipation) the average RTs for each participant, were not included in statistical analyses of RTs. Descriptive results are displayed in **Table 1**.

Analysis of Attentional Functioning

Attentional effects were evaluated by means of 2 (Alerting) × 3 (Orienting) × 2 (Congruency) repeated-measures ANOVAs of mean RTs and error percentages. The analysis of RTs showed the typical functioning patterns of each of the attentional networks, Congruency, $F(1,112) = 486.81$, $p < 0.001$, $\eta_p^2 = 0.81$; Alerting, $F(1,112) = 145.83$, $p < 0.001$, $\eta_p^2 = 0.57$; and Orienting, $F(2,224) = 169.72$, $p < 0.001$, $\eta_p^2 = 0.60$. Similarly, executive control was modulated by the other networks in RT, Alerting × Congruency, $F(1,112) = 11.68$, $p < 0.001$, $\eta_p^2 = 0.09$, and Orienting × Congruency, $F(2,224) = 23.36$, $p < 0.001$, $\eta_p^2 = 0.17$. A significant interaction was also found between Alerting and Orienting, $F(2,224) = 11.77$, $p < 0.001$, $\eta_p^2 = 0.09$, in RT. Regarding the analysis on response accuracy, the main effects of Congruency, $F(1,112) = 101.11$, $p < 0.001$, $\eta_p^2 = 0.47$, and Orienting, $F(2,224) = 9.90$, $p < 0.001$, $\eta_p^2 = 0.08$, were replicated, but not those of Alerting, $p = 0.102$. We also observed the typical interactions between Alerting × Congruency, $F(1,112) = 9.03$, $p = 0.003$, $\eta_p^2 = 0.08$, and Orienting × Congruency, $F(2,224) = 4.33$, $p = 0.014$, $\eta_p^2 = 0.04$; the Alerting × Orienting interaction, $F(2,224) = 2.93$, $p = 0.055$, $\eta_p^2 = 0.03$, was marginally significant. Therefore, the task showed the usual pattern of results.

Analysis of the Attentional Differences Between Non-Athletes and Soccer Players

More in line with the main aims of this study, the results of the 2 (Deliberate Sport Practice) × 2 (Alerting) × 3 (Orienting) × (2 Congruency) MANOVA revealed a main effect of Deliberate Sport Practice on RTs, $F(1,111) = 38.01$, $p < 0.001$, $\eta_p^2 = 0.25$, but

TABLE 1 | Mean (M) ± SD reaction times and error percentage (in parenthesis) for each experimental condition and group.

		No tone			Tone		
		Uncued	**No cue**	**Cued**	**Uncued**	**No cue**	**Cued**
Non-athletes (n = 54)	Congruent	802 ± 183 (2.31 ± 3.90)	815 ± 184 (2.93 ± 3.73)	758 ± 158 (2.31 ± 4.06)	744 ± 131 (2.01 ± 3.82)	713 ± 128 (1.77 ± 3.36)	699 ± 157 (2.16 ± 3.65)
	Incongruent	981 ± 221 (7.95 ± 8.34)	978 ± 227 (10.34 ± 12.72)	907 ± 207 (8.41 ± 9.47)	936 ± 195 (10.34 ± 8.32)	922 ± 200 (9.65 ± 10.14)	857 ± 204 (7.95 ± 10.18)
Soccer players (n = 59)	Congruent	657 ± 101 (1.69 ± 2.98)	660 ± 110 (2.05 ± 4.01)	628 ± 97 (1.41 ± 2.72)	619 ± 90 (2.19 ± 4.36)	590 ± 99 (1.69 ± 3.17)	579 ± 102 (0.92 ± 2.66)
	Incongruent	780 ± 125 (7.27 ± 8.49)	766 ± 125 (5.93 ± 7.20)	720 ± 122 (4.52 ± 6.39)	761 ± 113 (9.53 ± 10.82)	716 ± 108 (7.84 ± 10.03)	671 ± 92 (6.36 ± 8.02)

not on response accuracy ($p = 0.145$). Soccer players were 164 ms faster than non-athletes and also tended to show higher accuracy (4.28 and 5.67% error rates, respectively).

More importantly, our results revealed a positive association between deliberate sport practice and executive control. Soccer players showed reduced conflict compared to non-athletes with both response speed [$F(1,111) = 28.01$, $p < 0.001$, $\eta_p^2 = 0.20$] and response accuracy, although in this case, the difference was not significant ($p = 0.181$).

We also observed between-group differences in the functioning of attentional orienting, both in response speed, $F(2,222) = 4.31$, $p = 0.015$, $\eta_p^2 = 0.04$, and in response accuracy, $F(2,222) = 3.85$, $p = 0.023$, $\eta_p^2 = 0.03$. However, as shown in **Figure 2**, *post hoc* analyses showed no differences between soccer players and non-athletes in the overall orienting effect (uncued–cued), $p = 0.320$. Between-group differences (with faster RTs in the group of soccer players) were particularly evident in the no-cue condition, in which no temporal or spatial signal was presented that could be used as a reference for preparation. A similar effect was found in response accuracy, with a lower percentage of errors especially in the cued and no-cue conditions.

Finally, alerting was not significantly affected by Deliberate Sport Practice in either response speed ($p = 0.070$) or response accuracy ($p = 0.072$).

Finally, no relationship was observed between Deliberate Sport Practice and the interaction between executive control and the other attentional networks (all ps > 0.05).

DISCUSSION

The purpose of this study was to test the association between deliberate sports practice and attentional functioning, especially at early ages (10–12 years), given that in recent decades, there has been a growing interest in clarifying the relationship between physical exercise and cognition (McMorris, 2016). Specifically, our approach is novel in the analysis of the influence of predominantly open-skill sports (i.e., soccer) on executive control, in a context of complex interaction with other attentional networks (i.e., alerting and orienting).The study of these relationships from childhood to preadolescence is especially interesting, as it is a crucial period for sports initiation (e.g., Raya et al., 1993, in the case of soccer) and coincides with a key evolutionary stage in cognitive development in general and concerning attentional networks in particular (Casey et al., 2000; Rueda et al., 2004).

Regarding the functioning of attentional networks, our results replicated those of previous studies conducted using the ANT task (Mezzacappa, 2004) or the ANT-I (Callejas et al., 2004; Rueda et al., 2004) revealing the typical main effects of executive control, alerting, and orienting, as well as the interactions between them (Alerting × Conflict, Orienting × Conflict, and Alerting × Orienting). Our findings confirm that the ANT-I is a useful and valid tool for assessing attentional functioning in children aged between 10 and 12 years. The ANT-I is a task which demands a complex space–time interaction of

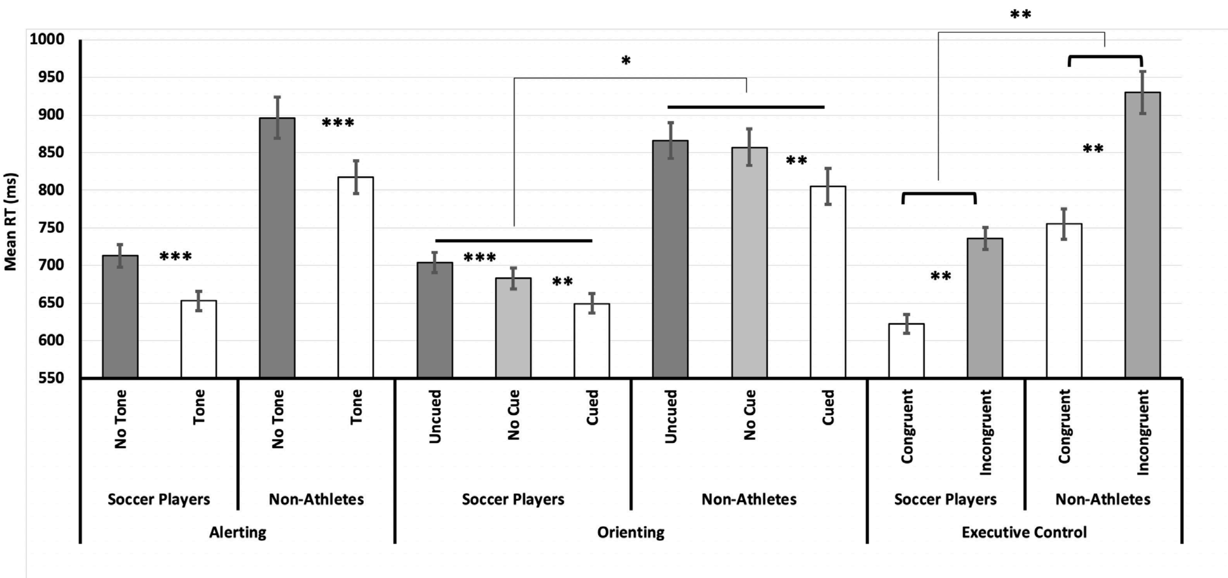

FIGURE 2 | Mean reaction time (RT) for each experimental condition used to measure each attentional function, as a function of Deliberate Sport Practice. For alerting, only no-cue trials were used to compute the means. Note that soccer players were faster in general than non-athletes and showed reduced interference (i.e., reduced difference between congruent and incongruent conditions). Error bars represent the standard error of the mean. *Indicates significant differences between groups and attentional conditions (* $p < 0.05$, ** $p < 0.001$, *** $p < 0.0001$).

visual and sound stimuli. In our opinion, it is more similar to the demands of many situations in the real environment and, specifically, in many sports setting. The complexity of the stimuli presented by the ANT-I requires the simultaneous functioning of all three attentional networks. We therefore consider that the methodological paradigm used to study the relationship between sports practice and executive control is more ecological than those previously proposed in other studies using tasks that evaluate the functioning of this network in isolation (e.g., Castelli et al., 2011; Davis et al., 2011; Chaddock et al., 2012).

Regarding the specific objectives of our study, we found that deliberate practice of an open-skill sport such as soccer was associated to faster and more accurate responses, although the accuracy result did not reach statistical significance. These findings are consistent with those reported by previous studies showing the benefits of aerobic fitness, inherent to regular sports practice, on response speed (see the meta-analysis by Voss et al., 2010). Our results are also consistent with the findings of Ballester et al. (2015, 2018) showing that deliberate soccer practice during preadolescence was positively associated with response speed, albeit those studies used a different cognitive task (i.e., the Psychomotor Vigilance Task).

More importantly, and focusing on the association between deliberate sport practice and the functioning of executive control, our results showed a lower level of conflict in the group of soccer players compared to their non-athletes counterparts. As stated in the section "Introduction," numerous studies have explored this relationship using different paradigms. In general, a pattern of results similar to that obtained in the present study has been observed. However, most studies used tasks suitable to measure executive control in isolation, independently from other cognitive functions (see reviews by Best, 2010; Guiney and Machado, 2013; de Greeff et al., 2018; Sanders et al., 2019). We consider that between-groups differences in executive control could be explained by the two dominant hypotheses in the study of the relationship between sports practice and cognitive functioning.

It is logical to argue that, though this variable was not measured in our study, the physiological demands of regular sport practice may have led to a better aero-anaerobic physical fitness in soccer players vs non-athletes (Ballester et al., 2018). In this regard, the cardiovascular fitness hypothesis (North et al., 1990; Voss et al., 2011) postulates that higher cardiovascular capacity, which is inherent to the regular practice of physical exercise, accounts for the cognitive improvement of individuals who exercise regularly due to physiological adaptations. Some examples of this are increased VO_2, increased brain-derived neurotrophic factor (BDNF), and increased cerebral blood flow (North et al., 1990; Voss, 2016). In fact, the reviewed literature offers ample evidence of the positive impact of an improvement in aerobic fitness on the executive function in children (Buck et al., 2008; Hillman et al., 2009; Chaddock et al., 2010, 2012; Castelli et al., 2011; Davis et al., 2011; Pontifex et al., 2011; Voss et al., 2011). However, there is also some evidence that cardiovascular fitness is not a physiological mediator for improved cognitive performance in children (e.g., see Etnier et al., 2006; Ballester et al., 2018; Sanabria et al., 2019). In our opinion, these discrepancies may be partially explained by the methodological variations between the different studies, which make their results difficult to compare.

In view of this, the observed better executive control in soccer players than in non-athletes could alternatively be explained by the cognitive component skills approach (Mann et al., 2007; Voss et al., 2010). In our case, it is important to note that optimal performance in externally paced sports such as soccer requires not only a good level of physical fitness but also the ability to quickly adapt and respond to the demands of complex and constantly changing situations. Thus, the systematic and structured practice of externally paced sports, such as soccer, involves the learning and practice of basic cognitive abilities to manage these situations. The cognitive component skills approach would imply that this learning would be transferred to other general or specific domains, as proven by previous studies (Best, 2010; Williams et al., 2011; Ballester et al., 2019). In this vein, Wang et al. (2013) observed that university students who practiced an externally paced sport (i.e., tennis) exhibited greater inhibitory control than those who practiced a self-paced sport (i.e., swimming). The specific demands of the soccer environment may require this "cognitive specialization" in attentional performance, given that players are exposed to situations where they have to select relevant stimuli in a complex environment and decide between several possible options under high time pressure (Abernethy et al., 1993; Williams et al., 1999; Voss et al., 2010).

Our results seem to show that the association between deliberate soccer practice and executive control occurs at early ages and in a complex cognitive evaluation context, where the response is conditioned by stimuli that require the simultaneous participation of other attentional networks (i.e., orienting and alerting). Likewise, we observed a connection between sport practice and the functioning of orienting. However, in-depth analyses of this interaction showed that the greatest benefit observed in the group of non-athletes was due to the fact that they were significantly slower than soccer players in the no-cue conditions, not that they processed the orienting signal differently. This is consistent with the existing literature, given that there is very little evidence linking systematic sport practice to spatial orienting. Previous studies have, rather, focused on the analysis of the acute effect of exercise on exogenous (e.g., Huertas et al., 2011, 2019; Sanabria et al., 2011; Llorens et al., 2015) or endogenous spatial orienting (e.g., Pesce et al., 2002, 2003, 2004, 2007a,b, 2011).

Finally, our study did not find any link between deliberate sport practice and the functioning of the alerting network. Although the existing literature is scarce and controversial, our results are in line with those described by Buck (2008) showing no between-groups differences in the alerting network (evaluated with the ANT) in preadolescent children classified according to their level of aerobic fitness. By contrast, Verburgh et al. (2014) found that, in a sample of young soccer players aged 8–16 years from teams of different levels, presenting the warning signal benefited the players in higher-level teams. Regarding vigilance, the studies by Sanabria et al. (2019) and Ballester et al. (2018) did not find that the differences in vigilance functioning were explained by the cardiovascular fitness hypothesis but, rather, that these differences were due to the type of sport practiced. This leads us to confirm again that, when analyzing the relationships between systematic sport practice and any cognitive function, it is essential to control the influence of the variables that can mediate in this relationship: both those related to the development of the physical fitness of the participants and those related to the level of expertise, skill, or experience in the practice of the sport. It would be interesting to conduct further studies analyzing phasic alerting while controlling for aerobic capacity, in order to verify whether this factor is a positive mediator of this attentional function.

Some of the controversial findings described in several studies regarding the relationship between regular sports practice and cognitive functioning could be explained by the different methodological approaches used. First, it is important to analyze the effect of the age of the participants given that, as shown by many studies, it modulates the functioning of the different attentional functions and may explain these differences. It should be noted that the orienting network (e.g., Wainwright and Bryson, 2002) and the executive control network (e.g., Rueda et al., 2004; Simonds et al., 2007) seem to become consolidated before the age of 10, whereas the alerting network seems to continue its development after this age (e.g., Rueda et al., 2004; Pozuelos et al., 2014). In view of this, it would be interesting to conduct further longitudinal studies or studies including different age groups to determine how systematic sports practice modulates the development of each network at different stages. Moreover, when explaining the association between deliberate sport practice and executive control and the rest of the attentional functions, it is important to describe the type of task used for its assessment, the level of complexity and cognitive demand, the interaction with other networks, and other aspects. In this regard, difficulties could arise when comparing our results with those obtained by Verburgh et al. (2014), given that they used the ANT, which measures alerting through visual signals, as opposed to acoustic signals used in the ANT-I and thus in our research. These differences in the specificity of the stimuli used to assess the various cognitive functions, in accordance with the cognitive component skills approach, may explain the controversy in the results of various studies (e.g., in soccer, visual warning signals are likely to be much more relevant and specific than acoustic warning signals).

Finally, we suggest that further research about the relationship between regular sports practice and cognition should consider both the role of the type of sport practiced (i.e., self-paced vs externally paced), linked to the cognitive component skills approach (Mann et al., 2007; Voss et al., 2010), and the practitioner's physical fitness, as proposed by the cardiovascular fitness hypothesis (North et al., 1990; Voss et al., 2011). This will allow assessment of the influence of each of these potential mediating factors in the development of every cognitive function studied. In this sense, one limitation of the present study is that its methodological design does not allow us to adopt a defined position in favor of either of the two hypotheses described above. The reason is that we consider that, as shown by previous studies, the soccer player group probably had a greater cardiovascular fitness level (e.g., Vänttinen et al., 2011; Plaza-Carmona et al., 2013; Ballester et al., 2015) and a better level of development of the attentional functions (Daus et al., 1989; Abernethy et al., 2001; Farrow and Abernethy, 2003) than the non-athlete group. In short, we believe that the contextual demands to which these players are regularly subjected in training and competition may lead to physical, physiological, perceptual, and cognitive adaptations and induce changes in the functioning of executive control and other cognitive functions.

Furthermore, our results could be partly explained by the existence of a self-selection bias in the sport context, the so-called "neuroselection effect," according to which individuals with better cognitive functioning choose more active and healthier lifestyles (e.g., Kanazawa, 2013; Belsky et al., 2015). According to this hypothesis, children who play soccer in high-level clubs could have higher development of certain cognitive abilities, such as executive control, which would facilitate their involvement in these types of open-skills sports. An important direction for further research might be to investigate the functioning of the attentional networks in different sport disciplines (self-paced vs externally paced) controlling both the athlete's level of expertise and the athlete's levels of cardiovascular fitness, in order to clarify their relative contribution to attentional performance. Given the cross-sectional nature of the present study, future research should also use experimental designs with random assignment of participants to the experimental and control groups in order to add more solid evidence about the causal effect of deliberate sport practice on executive functions.

CONCLUSION

Our results shed new light on the advantageous connection between the deliberate practice of externally paced sports during preadolescence and both response speed and executive control, as measured in a context of interaction with other attentional networks.

However, given the cross-sectional design of our study, our findings do not allow us to confirm the underlying reasons for the advantage observed in the cognitive performance of soccer players. Different hypotheses could explain our results. First, the potential higher physical fitness level of soccer players may have an influence on neurophysiological aspects that benefit executive control, in line with the cardiovascular fitness hypothesis. Additionally, athletes' executive control may also have been improved by repeated exposure to situations where these functions are in high demand, as proposed by the cognitive component skills approach. Finally, and according to the "neuroselection effect," sport practitioners probably had, before starting the training program, more active lifestyles and better cognitive function than their non-athlete counterparts, which would also contribute to their better cognitive functioning.

Independently of the moderators and mediators underlying this association, these findings are particularly relevant, as they highlight the need to promote physical-sports activity at an institutional level from an early age, given its positive impact on both physical and cognitive development. They also reinforce the recommendations issued by the World Health Organization (World Health Organization [WHO], 2010) on the regular practice of physical exercise. In view of our findings, we propose that, within the recommended parameters of physical activity intensity (i.e., moderate and intense for at least 60 min per day), it would be interesting to specify the following: the activity should involve perceptual–cognitive and decision-making processes (e.g., externally paced sports such as team, combat, or racket sports). In fact, as shown by the current literature (e.g., Tomporowski and Pesce, 2019), physical-sport activities with higher perceptual–cognitive demands seem to be the most beneficial at the cognitive level.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made readily available to all qualified researchers. Requests for access to the data should be addressed to CM at consuelo.moratal@ucv.es.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Research Ethical Committee from Catholic University of Valencia (UCV/2015/2016/22). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

CM: conception and design of the study, the data acquisition, analysis, and interpretation, drafting of the article and critical revision for important intellectual content with specific contribution regarding the physical activity–attention relationship, final approval of the version to be published, and agreement to be accountable for all aspects of the research. JL: contribution to the conception of the study, creation of the attentional test, the data analysis and interpretation, drafting and critical revision of the article for important intellectual content with specific contribution regarding attentional functioning issues, final approval of the version to be published, and agreement to be accountable for all aspects of the research. RB: data interpretation, drafting and critical revision of the study for important intellectual content with specific contribution regarding systematic sport practice issues, contribution to drafting the article, final approval of the version to be published, and agreement to be accountable for all aspects of the research. FH: main role in the conception and design of the study with a relevant role in project coordination and data acquisition, interpretation and critical revision of the article with specific contribution regarding the physical activity–attention relationship, final approval of the version to be published, and agreement to be accountable for all aspects of the research.

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MINI REVIEW
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The Implications of Motor and Cognitive Inhibition for Hot and Cool Executive Functions: The Case of Quadrato Motor Training

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Enabling the ceasing of ongoing or prepotent responses and the controlling of interference, motor inhibition facilitates the development of executive functions (EFs) such as thought before action, decision-making, self-regulation of affect, motivation, and arousal. In the current paper, a characterization is offered of the relationship between motor inhibition and the executive functioning system, in the context of a proposed division into predominantly affective (hot) and cognitive (cool) components corresponding to neural trajectories originating in the prefrontal cortex. This division is central to understanding the effects of a specifically-structured sensorimotor movement training practice, known as Quadrato Motor Training (QMT), on hot and cool EFs. QMT's effects on crucial mechanisms of integrating different EF components are discussed.

Keywords: motor inhibition, quadrato motor training, executive functions, self regulation, sensorimotor training

INTRODUCTION

Motor and cognitive development's close relationship (Sibley and Etnier, 2003; Pesce et al., 2016; Stein et al., 2017) is exemplified by the role of motor inhibition in the development of executive functions (EFs) (Hammond et al., 2012). As high-order cognitive functions, EFs (e.g., working memory, inhibition, planning, active monitoring, set shifting; Miyake et al., 2000; Diamond, 2013) contribute to goal-directed behavior while helping limit impulsive responses and regulate emotions (Riggs et al., 2013; Blair, 2016; Leshem, 2016; Leshem and Yefet, 2019). By inhibiting ongoing or prepotent responses and controlling attentional interference (Bickel et al., 2012; Bari and Robbins, 2013; Leshem and Yefet, 2019), motor inhibition facilitates EF development: thought before action, decision-making, and self-regulation of affect, motivation, and arousal (Barkley, 1997).

Therefore, motor inhibition, developed through experiences that involve body movements, is supposed to integrate motor and cognitive development. Motor experiences elicit different structural and functional changes, including physiological changes, such as enhanced cerebral blood flow (Stein et al., 2017) and changes in neurotransmitter release (Goldstein, 2006; Miranda, 2007; Winter et al., 2007). The interrelationship between motor and cognitive functions is further reflected by their simultaneous neuronal activation during complex or novel tasks requiring fast reactions or changing conditions (Diamond, 2000; Koziol et al., 2014; Leisman et al., 2016; Stein et al., 2017).

This mini-review characterizes the relationship between motor inhibition and EFs in the context of a proposed division into predominantly affective and cognitive components. This division is central to understanding the effects of structured movement practices on EF-based abilities.

FUNCTIONALITY- AND COGNITIVE-BASED DIVISIONS IN EXECUTIVE FUNCTIONING

EFs are traditionally considered purely cognitive top-down processes. They are typically categorized into either abstract cognitive functions (e.g., general attention abilities, such as switching attention; Heaton et al., 1993; Kenemans et al., 2005) or those that operate in highly motivated or emotionally salient contexts (Zelazo and Müller, 2002). Accordingly, a distinction has been proposed between "cool EFs," elicited by abstract, decontextualized tasks lacking significant affective or motivational components (Zelazo and Carlson, 2012; Tsermentseli and Poland, 2016), and "hot EFs" (Zelazo and Müller, 2002), involved in emotions, beliefs, or desires, such as those associated with reward and punishment, social behavior, and emotional components of decision-making (Leshem, 2016).

Neuroscientific studies suggest a distinction between cool and hot EFs, reflected in how they are traditionally measured (Bechara et al., 2000; Berlin et al., 2004; Anderson, 2010; De Luca and Leventer, 2010; Zelazo and Carlson, 2012). Patients with specific brain damage (e.g., orbitofrontal cortex) may show intact cool EFs (assessed by classical tests such as the WCST) but impaired hot EFs (assessed by tests like "the Iowa gambling task" (e.g., Bechara et al., 1994) or vice versa (Zelazo and Carlson, 2012).

This functional distinction may reflect a structural one, as neural systems underlying EFs appear to vary as a function of motivation. It is generally accepted that EFs are largely governed by the pre-frontal cortex (PFC) and its reciprocal interactions with other cortical and subcortical brain regions (Diamond, 2000; Miyake et al., 2000; Blair, 2016). Accordingly, hot and cool EFs are theorized to be associated with differential neural trajectories originating in ventral-medial and dorsolateral PFC sections, respectively (Zelazo and Müller, 2002).

Hot EFs are generally associated with the paralimbic cortex, comprised of the ventromedial PFC (VMPFC) and caudal orbitofrontal cortex (OFC). Closely connected to limbic structures (e.g., amygdala, hypothalamus) these areas provide descending input to midbrain structures (Barbas, 2000) and are involved in inhibition, emotion, and reward processing – suggesting a behavioral self-regulation role. Numerous case studies illustrating the effects of damage to these areas support this notion (Stuss and Levine, 2002; Fellows, 2004; Bechara, 2005).

In contrast, cool EFs are thought to recruit the lateral PFC, including the dorsolateral PFC (DLPFC), involved in attentional control, planning, working memory, spatial and conceptual reasoning, and learning (Stuss and Levine, 2002; Fellows, 2004; Banfield et al., 2004; Toplak et al., 2005; Crews and Boettiger, 2009).

Moreover, distinct EF components appear to demonstrate different developmental trajectories. Age-related improvements seem to emerge later and more gradually for hot EFs than cold, suggesting varied development courses. EFs are known to develop both linearly and nonlinearly during childhood and early/late adulthood, associated with underlying neural development and maturation (Best and Miller, 2010; Taylor et al., 2015). Progressively less recruitment of PFC regions is normal with increasing age (Somerville et al., 2011), presumably due to more diffuse neural engagement and less specialization at younger ages (Luna et al., 2013; Casey, 2015). As the brain continually reorganizes, mainly during adolescence, necessary neural connections are strengthened and unnecessary ones are pruned, creating more efficient focal recruitment of PFC regions (Shulman et al., 2016). According to the orthogenetic principle (Werner, 1978), executive functioning may be an initially unified construct (Wiebe et al., 2008; Hughes et al., 2009; Wiebe et al., 2011) that differentiates and specializes over time (Miyake et al., 2000; Johnson, 2011; Howard et al., 2015), producing distinct hot and cool EFs.

Deficits in hot and cool EFs may engender different psychopathologies and developmental outcomes (Anderson, 2002; Sonuga-Barke, 2005). When brain reorganization processes do not progress normally, diffuse engagement of neural regions may continue, resulting in insufficiently differentiated EFs (Johnson, 2011; Zelazo and Carlson, 2012). Likewise, if neural circuitry is damaged due to extrinsic injury, resulting behaviors can reflect earlier stages of EF development; such clinical expressions generally include disruption in both hot and cool EFs, such as deficits in delay gratification, inability to anticipate consequences, and verbal and behavioral disinhibition (Zelazo and Carlson, 2012).

INTEGRATION BETWEEN HOT AND COOL EFS IN ADAPTIVE FUNCTIONING

While distinct, hot and cool EFs also appear interdependent, working together in a coordinated system (Zelazo and Carlson, 2012). Dysfunction in both hot and cool EFs is apparent in a broad range of neurodevelopmental and psychopathological conditions (Snyder et al., 2015; Malloy-Diniz et al., 2017) such as autism (Gilotty et al., 2002; Luna et al., 2007; Johnston et al., 2019), ADHD (Swanson, 2003; Tsal et al., 2005; Barkley, 2010; Stern et al., 2017), PTSD (Aupperle et al., 2012; Olff et al., 2014) and anti-social personality disorder (Morgan and Lilienfeld, 2000; Ogilvie et al., 2011).

Known to affect systems associated with either hot or cool EFs at the neural level, these disorders nevertheless appear to manifest both components at the clinical and behavioral level, suggesting interdependency. For example, while cool EFs are a focus of autism spectrum disorder research (Kouklari et al., 2019), a crucial role for hot EFs has also been proposed (Kouklari et al., 2019). Zelazo and Müller (2002) theorize that autism is characterized by primary deficits in hot EFs with secondary impairments in cool EFs. Conversely, anti-social personality disorder and/or psychopathic traits are generally associated with hot EF deficits, such as response reversal, sensitivity to reward, and affective decision-making (Mitchell et al., 2002; Blair, 2010; Carré et al., 2013) despite mixed findings in both EF deficits among individuals exhibiting anti-social behavior (see De Brito et al., 2013; Delfin et al., 2018).

Interdependency between hot and cool EFs suggests that impairments in one EF type may lead to impairments in the other. Therefore, integration and balance between the two EF components and their underlying neural systems may be essential to adaptive functioning and well-being. A specific form of structured sensorimotor training may play a significant role in achieving this integration.

ENHANCING EXECUTIVE FUNCTIONING THROUGH MOTOR INHIBITION: QUADRATO MOTOR TRAINING AND THE ABILITY TO WAIT

Quadrato Motor Training (QMT) is a non-aerobic, coordination-demanding, and cognitively-engaging movement practice developed by Patrizio Paoletti (Ben-Soussan et al., 2015b). Practitioners are required to alternate between dynamic movements and static postures, while focusing attention and awareness on their bodies in the present moment and excluding all the other thoughts. QMT is conducted on a 50 × 50 cm square known as the Quadrato space. Its corners are labeled with the numbers 1–4. Practitioners are required to either produce or inhibit a motor response in the Quadrato space, based on specific verbal instructions presented in an audio recording. The motor responses are steps in one of three possible directions: right or left; forward or backward; or diagonally. For example, a verbal instruction can be "1–2," which directs the practitioner to take a step forward from corner number 1 to corner number 2. When the two numbers of the verbal instruction are the same (e.g., "1–1"), the practitioner must inhibit the impulse to move upon hearing the voice command and wait for the next instruction. The inhibitory control (cognitive and motor) required to make a decision based on cognitively processed information related to the specific verbal instruction is one of the main features of the QMT. Inhibitory control is also involved in continuing to the next instruction rather than stopping when a mistake occurs (De Fano et al., 2019).

Diamond and Ling (2016) claimed that practices aiming to improve cognition in general, and EFs in particular, must not only recruit cognitive resources, but challenge them continually. It therefore stands to reason that QMT, which is associated with continual cognitive challenges, would improve cool EFs. Indeed, this was demonstrated in previous research using abstract, decontextualized problem-solving tasks absent significant affective or motivational components, such as the Alternate Uses Test (AUT; Guilford, 1967; Ben-Soussan et al., 2013, 2015a; Venditti et al., 2015; Piervincenzi et al., 2017). Both single session and protracted QMT practice have produced increased ideational flexibility (Ben-Soussan et al., 2013, 2015a; Venditti et al., 2015) — the ability to produce creative ideas by shifting from one meaningful category to another (Diamond, 2013). A prominent measurable dimension of divergent thinking (Guilford, 1967), this ability to change perspectives relies on inhibitory control; in order to effectively "think outside the box," other perspectives previously loaded in working memory must be inhibited (Diamond, 2013).

QMT-induced gains in ideational flexibility likely result from motor and cognitive inhibition acquired through the cognitively-engaging motoric practice. Indeed, interventions involving only the cognitive component of QMT practice (participants responding verbally to QMT instructions rather than with movement) did not significantly change ideational flexibility (Ben-Soussan et al., 2013, 2015a). Conversely, practicing a motor component similar to the QMT (i.e., taking steps) but without cognitive effort (i.e., reduced reaction choices) also did not change ideational flexibility (Ben-Soussan et al., 2013, 2015a; Venditti et al., 2015). This suggests that neither motor experience, nor cognitive challenge, alone is sufficient to enhance cool EFs. Benefits appear to result from the combination, as evidenced by physical activity research indicating that more effective improvement in executive functioning resulted from combined cognitive, physical, and emotional engagement, than on cognitive stimulation or physical activity alone (Pesce, 2012; Tomporowski and Pesce, 2019).

Moreover, cognitive benefits of QMT are not limited to cool EFs. QMT also enhances self-efficacy (Paoletti et al., 2017; Piervincenzi et al., 2017) and affect balance (Paoletti et al., 2017), which are both closely related to higher-order cognitive functions and self-regulation (Schunk and Zimmerman, 2007; Kessler and Staudinger, 2009).

Research shows that one week of intense QMT combined with a breathing meditation enhances general self-efficacy, compared to the breathing meditation alone (Paoletti et al., 2017). Moreover, the combination of QMT and breathing meditation improved affect balance, shifting it toward more positive emotions (Paoletti et al., 2017). These results support the notion that cognitively-engaging movement-based experiences can improve hot, as well as cool, EFs.

The impact of motor-cognitive-affective activity elicited by QMT was explored using semi-structured oral interviews (Ben-Soussan et al., 2017). Following QMT practice, participants report increased experiences of attention, mindfulness, ability to wait, positive emotions, and bodily harmony. They also report experiences of spontaneous visualization, intuition, and sense of wonder, which have been categorized as altered states of consciousness and are similar to experiences commonly elicited during meditation practices (Wallace, 1999). This further supports QMT's potential enhancement of hot EFs. QMT may be considered an embodied cognitive training and "mindful movement" (Ben-Soussan et al., 2014; De Fano et al., 2019). Like other mindfulness-based practices, mindful movement is mainly characterized by a focus on movement in the present moment while excluding other thoughts, inclusion of some form of body movement, and focus on breathing (De Fano et al., 2019); nevertheless, the existing studies related to QMT of which we are aware did not provide direct, explicit instructions related to these components. Yet, each participant clearly had to be mindful of the location of their body in the Quadrato space and, therefore, we cannot exclude the importance of body awareness and interoception, which, in turn, can affect hot EFs. Russell and Arcuri (2015) suggest mindful movement practices involve key aspects of mindfulness such as preparation and execution of movement, regulation of attention, working memory, and their relationship to mind-wandering, an opposite construct to mindfulness (Mrazek et al., 2012). QMT involves each of these aspects: regulation of divided attention, working memory updating (e.g., noting one's current location to know where to move to next), and prevention of mind-wandering via a need to be "in the here and now" due to constantly updating commands (Ben-Soussan et al., 2014; De Fano et al., 2019). Mindful movement training engages "higher-order" inhibition and response selection that underlie attention and cognitive control) that requires moment-by-moment sensorimotor updating (Clark et al., 2015; Kimmel and Rogler, 2018). In line with this, QMT requires second-by-second mindful awareness for attending the upcoming next command (Ben-Soussan et al., 2014; De Fano et al., 2019).

QMT AS A MEANS OF INTEGRATING COOL AND HOT EFS

QMT's potential benefits for both cool and hot EFs are further supported by research on functional and structural brain changes. As noted above, cool and hot executive processes are, respectively, associated with specific areas of the PFC. Those areas are interconnected with numerous regions throughout the brain, associated with changes in behavior and cognition that fall within the broader area of EFs (Barbas and Zikopoulos, 2007). Goal-directed, purposeful EFs support cognitive and affective states with purported association with differential neural trajectories originating in dorsolateral, and ventral and medial, PFC sections, respectively (Zelazo and Müller, 2002; Blair, 2016).

Accurate execution of QMT involves concurrent motor activation and response inhibition. In turn, response inhibition is mediated both by the cool EF system responsible for planning, control, and execution of voluntary movements, and the hot EF system associated with processing and regulating behavior involving emotional content (Bush et al., 2000; Etkin et al., 2011). Executing specifically structured movements can lead to integrated communication between brain areas associated with cognition and emotion. Accordingly, QMT generates changes in neural activities, such as frontal alpha activity and contingent negative variation amplitude (Ben-Soussan et al., 2013; Lasaponara et al., 2019), known to be closely related to planning, decision making, and moral judgment (Harung et al., 2009; Travis et al., 2011), all of which require both cool and hot EFs; thus supporting the hypothesis that QMT can improve cool and hot EFs.

Ben-Soussan et al. (2013) showed that improvements in ideational flexibility were concurrent with enhanced intra- and inter-hemispheric connectivity, expressed in increased synchronization between brain regions located in the same or different hemispheres, respectively. Increased neural synchronicity was specifically related to bilateral fronto-temporal networks and frontal areas in the alpha band (8–12 Hz), and was confirmed in a later study by the same group (Lasaponara et al., 2017). Accordingly, QMT may positively affect cool EFs by increasing frontal alpha connectivity. One should keep in mind that so far this line of studies examined changes in baseline EEG activity rather than functional EEG activity during a behavioral task. Future studies should examine this also during task conditions.

These findings align with research showing enhanced attention induced by an attentional training program and mediated by increased functional connectivity in frontal regions (Liu et al., 2019). Similarly, Basharpoor et al. (2019) found a positive association between high executive functioning, including inhibitory control, and increased alpha activity in frontal regions of right and left hemispheres. Increased functional synchronicity in the alpha band was found not only in relation to frontal areas; following QMT, the limbic network was also found more synchronized with both hemispheres' frontal areas, compared to pre-training (Lasaponara et al., 2017).

As noted above, the limbic system is involved in emotional experience, motivation, learning, and memory formation (Isaacson, 1982; LeDoux, 2000). In this regard, there is a line of research within the theories of consciousness and high-order cognition that argue that emotions are not built-in but are higher-order states instantiated in cortical circuits. They are not triggered but created. Because the limbic cortices are strongly interconnected and position in hierarchical cortical information flow, they can contribute to the neural basis of conscious access and may be a source of emotional experience and influence the coordination and regulation of cognitive-emotional processes (Chanes and Barrett, 2016; Kovner et al., 2019; for extensive reading see Barrett, 2017; LeDoux and Brown, 2017). The QMT-associated increase in limbic-frontal functional connectivity may reflect its effectiveness in integrating the "coolest" of cognitive functions with the "hottest." Possibly promoting adaptive behavioral responses, this could underlie the QMT-induced increase in general self-efficacy and affective balance (Paoletti et al., 2017; Piervincenzi et al., 2017).

Notably, QMT has been found to increase white matter integrity in several tracts [e.g., superior longitudinal fasciculi (SLF) and uncinate fasciculi (UF); Piervincenzi et al., 2017] that connect the PFC with the medial temporal lobe (Kovner et al., 2019), which is associated with numerous disorders of maladaptive behavior and low emotional control, including obsessive-compulsive disorder and PTSD (Jenkins et al., 2016). Further, enhanced SLF white matter integrity was positively associated with improvements in ideational flexibility (Ben-Soussan et al., 2015a) and general self-efficacy (Piervincenzi et al., 2017). QMT-induced improvement in UF white matter integrity was also positively correlated with first-person reports of experiencing reduced mind-wandering (Ben-Soussan, 2019). These findings support the possibility that QMT facilitates integration between cool and hot EFs. Future studies should examine whether QMT-induced enhanced ideational flexibility and self-efficacy, as well as reduced mind-wandering, in healthy adults could potentially ameliorate maladaptive pathologies such as in PTSD or OCD.

CONCLUDING REMARKS

This mini-review presented a proposed division for predominantly cool and hot EFs and introduced QMT, a sensorimotor training paradigm, as a means of enhancing healthy development (Levit-Binnun et al., 2013) by integrating these EF components.

QMT's requirement of smoothly executed goal-directed behaviors in response to predetermined verbal instructions separated by interstimulus intervals (ISIs), which are known to increase the duration of attention (Leckart et al., 1970), differentiates it from other mindful movement practices (Ben-Soussan et al., 2019).

QMT requires second-by-second response inhibition (Ben-Soussan et al., 2014; De Fano et al., 2019), and thus requires high order cognitive function, which is more related to cool EFs. Notwithstanding, evidence suggests training that requires attentional abilities also leads to enhancement of hot EFs. As hot EFs may benefit from physical activity, especially when executed in emotionally evocative settings, future research is encouraged to uncover the effects of physical activity on a broader range of EFs.

AUTHOR CONTRIBUTIONS

TB-S and RL conceptualized the manuscript. TB-S, RL, and AD wrote the manuscript.

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REVIEW
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Cognitive-Motor Dual Task Interference Effects on Declarative Memory: A Theory-Based Review

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Bouts of exercise performed either prior to or immediately following study periods enhance encoding and learning. Empirical evidence supporting the benefits of interventions that simultaneously pair physical activity with material to be learned is not conclusive, however. A narrative, theory-based review of dual-task experiments evaluated studies in terms of arousal theories, attention theories, cognitive-energetic theories, and entrainment theories. The pattern of the results of these studies suggests that cognitive-motor interference can either impair or enhance memory of semantic information and the manner in which physical activity impacts working memory within executive processing appears to explain disparate outcomes. The integration and timing of physical movements in concert with the type of information to be encoded and remembered appears to be a critical requirement for learning. These observations have implications for the role of physical activity in education, rehabilitation, and gerontological settings.

Keywords: executive function, embodied learning, long-term memory, attentional allocation, memory consolidation, physical activity, arousal theory

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INTRODUCTION

Routine, long-term chronic exercise is known to alter physical and mental functions. There is considerable evidence that exercise training benefits brain health and promotes improvements in information processing speed, executive function, and attention (Erickson et al., 2015). Historically, these augmentations have been explained in terms of adaptation of neurological structures and processes. There is compelling evidence for causal relations between exercise training and changes in brain structures and neurotrophic factors (Hillman et al., 2017). These findings have led researchers to consider a dose-response relation between exercise and mental function. Recent emphasis has been placed on psychological processes that may play a role in explaining the exercise-cognition relation. Reviews of the exercise literature reveal the importance of exercise interventions that engender goal-setting, mental engagement, and personal relevance (Diamond and Ling, 2016, 2020; Vazou et al., 2016). An examination of chronic exercise training experiments that made direct comparisons between interventions that emphasized routine aerobic or strength-training routines and multicomponent interventions that combined exercise training with cognitive training suggested that there are added benefits from multicomponent interventions (Tomporowski and Pesce, 2019), explaining the added benefit in terms of the presence of dual-task demands that optimize physical and mental challenge. Hypotheses were made concerning the importance of instructional methods and the necessity for varying the manner in which individuals process information, make decisions, select movements, and experience the consequences of their actions.

The mental operations that underlie dual- and multicomponent task performance have been studied extensively and several theories have been proposed to explain how individuals optimize decision making when placed in conditions in which two or more tasks are performed simultaneously (see historical review Wickens, 2008). In these theories, the roles of executive function (e.g., working memory, switching, and inhibition) are central to explaining how people deal with cognitive workload demands. In the main, theorists tend to view executive function in terms of "cool" information processing; that is, decision making and learning based on the manipulation of abstract concepts, number, or letters (Hongwanishkul et al., 2005; Brock et al., 2009). Less often is executive function described in terms of "hot" information processing, which refers to the affective responses that are evoked by motivationally and emotionally meaningful instructional contexts (Kerr and Zelazo, 2004; Zelazo and Kesek, 2010). This distinction is particularly relevant when considering conditions designed to pair emotionally laden physical activities with cognitive tasks. For example, exergames that couple exercise such as ergometer cycling with memorization of foreign language words embedded in video-scenes (see review Stojan and Voelcker-Rehage, 2019). Under these conditions, cognitive-motor interference (CMI) may occur. A task-classification system developed by Plummer et al. (2013) describes nine dual-task conditions and their possible outcomes: "(1) no interference (performance of either task does not change relative to single-task performance); (2) cognitive-related motor interference (cognitive performance remains stable while motor performance deteriorates); (3) motor-related cognitive interference (motor performance remains stable while cognitive performance deteriorates); (4) motor facilitation (cognitive performance remains stable while motor performance improves); (5) cognitive facilitation (motor performance remains stable while cognitive performance improves); (6) cognitive priority trade-off (cognitive performance improves while motor performance deteriorates); (7) motor-priority trade-off (motor performance improves while cognitive performance deteriorates); (8) mutual interference (performance of both tasks deteriorates); or (9) mutual facilitation (performance of both tasks improves). The pattern of CMI likely depends on several factors, including the types of tasks; levels of difficulty; instructions regarding which, if any, task to prioritize; and the characteristics of the person performing the task (e.g., cognitive and motor abilities, fear of failing, and distractibility)."

Central to the present review is the influence of the type of physical activity that is paired with learning semantic memory tasks. Exercise-induced arousal has long been considered a vehicle to boost attention and learning. Individuals who intentionally cycle on ergometers or walk on treadmills while reading, listening to podcasts, or viewing language instruction videos often believe that the material will be retained better when accompanied with physical activity. Indeed, a commercial industry has emerged that promotes the benefits of exergaming, which pairs exercise with learning tasks. As a result, some educators have considered the value of embedding in-class physical activities into their academic curricula (Mavilidi et al., 2018b). Given the multiple outcomes associated with CMI, it is deemed important to examine studies that have been conducted that pair physical activity with the encoding of semantic information.

The impact of individual bouts of exercise on cognition has been studied extensively and numerous reviews and meta-analyses consistently report temporary improvements in executive function and memory (Chang et al., 2012; Hillman et al., 2019; Lambourne and Tomporowski, 2010). These reviews, however, evaluate studies designed to evaluate how a bout of exercise impacts later cognitive processing. Lacking is information concerning conditions in which physical movement and cognitive processing occur simultaneously and how these dual-task conditions influence executive functions and affect the strength of memory encoding. A close inspection of the separate and interactive roles of hot and cool forms of executive function may elucidate how bouts of exercise facilitate memory storage. Presently, consolidation theory is the leading explanation for the transfer of information from short-term to long-term memory. Numerous laboratory studies highlight the role stressors play on the activation of the amygdala and the initiation of molecular time-locked processes involved in long-term potentiation that occur at the neuronal level that promote memory storage (McGaugh, 2015; Roig et al., 2016; Loprinzi et al., 2017). Studies conducted primarily with animals show that environmental stressors such as electrical shock and stimulant drugs enhance memory for events preceding stressors (McGaugh, 2000). Of note, proponents of cool and hot executive function make a distinction between the impact of environmental stressors that elicit reflexive stress responses and bottom-up sensory inputs to the amygdala (which negatively impact executive function) and learning tasks that create a context of challenge and problem-solving that activates orbitofrontal cortex and other medial brain regions (Zelazo and Carlson, 2012). While exercise does stress the systems of the body, the pattern of activity differs from those elicited by threating environmental stressors that elicit widespread affective response patterns (i.e., startle, freezing, piloerection, and facial expressions of fear; Dishman and Jackson, 2000). Thus, bouts of exercise that provide a context for skill development may lend themselves toward positive affective experiences, engender goal-directed motivated action plans, and maintain mental engagement.

The cognitive benefits derived from long-term chronic exercise training emerge from repeated, individual exercise bouts. As such, a close examination of dual-task studies that combine exercise in a single session or over a limited number of sessions with the encoding and retention of semantic information, may provide insight as to why long-term chronic experiments have shown added benefits from multicomponent interventions. Of particular interest is the identification of specific methodological factors that either may facilitate or compromise long-term memory. Interpretation of these factors could serve to bolster contemporary theory development, as well as to enhance clinical applications of basic science to targeted populations.

METHODS

Considerable research has examined task interference that results from attempts to deal with two or more cognitive tasks (e.g., performing a mathematics problem while listening to an ongoing conversation). The focus of the present review is on experiments in which dual-task conditions include a cognitive task (i.e., memorization) while engaged in physical activity (e.g., exercise). Sixteen experiments were retrieved following topical key-term searches. Search terms included: Acute exercise AND perceptual memory, episodic memory, associative memory, instrumental learning, relational learning, consolidation, procedural learning, implicit learning, action-perception learning, embodied learning, declarative memory, sematic memory, spatial memory, emotional memory, entrainment memory, sensory memory, iconic memory, echoic memory, imagery, dual-coding theory, eidetic memory, long-term potentiation, prospective memory, and meta-memory. Sources of studies published between 1985 and 2019 included Pubmed, Scopus, EBSCO, Google Scholar, and personal literature bases. Studies selected were restricted to those employing bouts of exercise or physical activities that require controlled actions of major muscle groups and induce a physical workload (e.g., walking, running, classroom activities, and sport skills) while encoding words into long-term memory. Study designs included single-trial and brief multi-trial experiments. Experiments evaluating balance and fine psychomotor movements were excluded. The purpose of the present selective review is to evaluate examples of dual-task exercise interventions that are representative of specific theories of long-term memory. Our intent was not to conduct a systematic review or a meta-analysis but rather to focus on methods employed in interventions designed to influence long-term memory and learning.

RESULTS

A cursory evaluation of the methods and outcomes in these experiments revealed considerable variation, with several studies demonstrating dual-task costs when exercise was performed simultaneously with encoding and other studies providing evidence of long-term memory enhancement (see **Table 1**). In an attempt to reconcile the different outcomes observed among these studies, the theoretical assumptions that guided the protocols used in individual experiments were evaluated and study outcomes were appraised. Experiments that have examined dual-task conditions in which exercise is performed simultaneously with the encoding of semantic information have been conducted to test arousal theory, attention theory, cognitive-energetic theory, and entrainment theory. It is recognized that there is considerable overlap among these theories. Nevertheless, each theory emphasizes a specific theme, or construct that guides the methods and tests that are employed by researchers. The main characteristics of each of these theories are provided in **Table 2**.

Arousal and Neuropsychological Theories

Increases in physical activity lead to a cascade of metabolic responses that signal brainstem nuclei central to the activation of noradrenergic and serotonergic systems that modulate brain activity, particularly in the prefrontal, and parietal cortices (Robbins, 1997; McMorris, 2016). Increased arousal is purported to enhance cognitive processing by altering the signal-to-noise ratio of neurological systems which, in turn, enhances attention, stimulus selection, and decision making (McMorris and Hale, 2015). The facilitative effects of individual bouts of exercise on information-processing speed have been explained in terms of the changes in central nervous system neurotransmitter systems that modulate brain activity (McMorris and Hale, 2015). The relation between arousal and cognitive function has been described in terms of an inverted-U function in which mental performance is enhanced with moderate, but not high, levels of arousal (McMorris and Graydon, 2000; McMorris and Hale, 2015). Heavy exercise elicits a broad spectrum of metabolic changes, peripheral and central fatigue, impaired motor control, and psychophysical perception alteration.

Evidence obtained from neuropsychology research and theory has been drawn upon to explain the relation between acute exercise and long-term memory storage. Comprehensive reviews of potential mechanisms have focused on the impact of physiological arousal prior to and following encoding periods (Roig et al., 2013; McGaugh, 2015; Loprinzi et al., 2017). Following contemporary neuro-biological descriptions of the brain substrates that underlie the formation and storage of memory engrams (e.g., hippocampus, amygdala, and cerebral cortices), researchers have attempted to link acute exercise to specific brain structures and functions (Loprinzi et al., 2017; Hillman et al., 2019). Of particular interest to the present review is the impact of arousal occurring during encoding processes and whether the after-effects of arousal influence memory consolidation.

Arousal Research: Experimental Evidence

Several experiments have focused on individual exercise bouts performed at intensities that promote aerobic metabolic energy production. A study conducted by Soga et al. (2017) had young adults perform an ergometer cycling protocol during which individual participants pedaled for 5 min. The workload was then gradually increased to a target heart rate (60–70% HR maximum), which is considered moderate intensity aerobic exercise. Cycling continued throughout a 7-min encoding phase during which participants performed a source memory task that involved viewing 160 pictures composed of 80 objects and 80 animals. Following a 5-min break from cycling, the participant completed a recognition task that included the 160 pictures viewed and 80 new pictures. The participant judged whether the item was old or new (familiarity judgement) and,

TABLE 1 | Selected studies that assess the effects of cognitive-motor interference on long-term memory.

Authors	Age (years)	Number	Intervention type	Memory task & test	Retention interval	Comparison conditions	Results
				Arousal and Neuropsychological Theories			
Soga et al., 2017	22	20	Cycling (12 min) Moderate intensity 60–70% HR_{max}	Visual source memory task Retrieval	5 min	Within subject	DTCs[1] lower item recognition accuracy
Frith et al., 2017	22	88	Treadmill running (15 min) Vigorous (RPE 16-20)	Auditory Verbal Learning Task Prospective Memory	20 min 24 h	Control Pre-[3] encoding Post-[4] encoding	20 min: Free call Pre[3] > SIM/ Control 24 h: Recognition Pre > SIM/ After
Sng et al., 2018	23	88	Treadmill walking (15 min) Preferred pace Moderate intensity 58% HR_{max}	Auditory Verbal Learning Test Prospective memory	20 min 24 h	Control Pre- encoding Post- encoding	20 min: Free recall Pre > SIM & Post Control > Post 24 h: Recognition Pre > SIM & Post Attribution Pre > Post Control > Post
Tomporowski et al., 2017	22	24	Isometric hand grip (100 s) $50\%_{max}/10\%_{max}$	Visual word list Free recall Recognition	Immediate Delayed (5 min)	Within subject	DTCs during encoding: Lower word recall & recognition
				Attention Theories			
Lindenberger et al., 2000	60–70 40–50 20–30	47 45 48	Walking (170 s) (Simple/Complex)	Auditory word list Serial recall	10 s	Standing Sitting	DTCs increased with age DTCs in young
Li et al., 2001	60–75 20–30	40 37	Walking (Adapted speed/ Complexity)	Auditory word list Serial recall	10-s	Single task	DTCs increased with age
Epling et al., 2016	28	12	Vigorous running (5 min) (Adapted speed)	Auditory word list Free recall	Immediate	Single task	DTCs for words
Green and Helton, 2011	22	12	Traverse wall climbing (3 min)	Auditory word list Free recall	Immediate	Single task (Seated)	DTCs for words
Darling and Helton, 2014	27	12	Traverse wall climb (5 min)	Auditory word list Free recall	Immediate	Single task (Seated)	DTCs for words
				Cognitive Energetic Theories			
Toumpaniari et al., 2015	4–5	67	Animal imitation Gesture Verbal repetition	Visual word-pair list Cued recall	4 weeks	Seated	SIM[2] > Gesture > Seated
Mavilidi et al., 2016	4–5	87	Animal imitation movement to spatial locations (30 min) Running (30 min)	Object name-location paired association Name- location recall	Immediate 5 weeks	Seated observation	Immediate: SIM = Run > Seated Delayed: SIM = Run > Seated
Mavilidi et al., 2017	4–5	86	Running to spatial locations (10 min) Running (undirected) (10 min)	Object name-location paired association Name-location recall Recognition	Immediate 6 weeks	Seated observation	Immediate + delayed: SIM > Run > Seated
Mavilidi et al., 2018a	4–5	120	Running, jumping, skipping along spatial number line (15 min) Running (15 min)	Counting Number line estimation Block counting Numerical magnitude comparison Numerical identification	Immediate 6 weeks	Seated observation Control	Immediate + delayed: IPA[5] > NIPA[6]
Schmidt et al., 2019	8–10	104	Animal imitation Verbal repetition	Auditory-Visual word-pair list Cued recall	Immediate	Seated	IPA[5] & NIPA[6] > Seated
				Entrainment & Embodied Learning Theories			
Schmidt-Kassow et al., 2013	22	81	Cycling (30 min) 69% HR_{max}	Auditory word list Cued recall	48 h	Seated rest Pre exercise	SIM > Rest/Pre
Schmidt-Kassow et al., 2014, Exp #1 Exp #2	22 22	18 31	Treadmill (30 min) Light intensity Treadmill (30 min) Light intensity	Auditory word list Cued recall Auditory word list Cued recall	24 h 24 h	Within subject Within subject	SIM > Rest SIM > Rest

DTCs[1] = Dual-Task Costs; SIM[2] = Simultaneous; Pre[3] = Exercise prior encoding; Post[4] = Exercise after encoding; IPA[5] = Integrated physical activity; and NIPA[6] = Nonintegrated physical activity.

TABLE 2 | Central assumptions of theories prompting dual-task physical activity research.

Arousal Theories
Assumptions: Metabolic activity increases with physical activity and results in alterations in brain neuromodulation.
Hypotheses: Exercise-induced arousal affects cognition in an inverted-U fashion and mental performance is enhanced with moderate, but not high, levels of arousal.

Attention Theories
Assumptions: Attention serves to "gate" what sensory experience enter consciousness and how it is manipulated in working memory.
Hypotheses: Interference among items held in short-term working memory compromises transfer into long-term memory.

Cognitive-energetic Theories
Assumptions: There is an interrelation between top-down cognitive control and bottom up sensory input and processing.
Hypotheses: Mental resources are allocated in ways that optimize behavioral actions and their consequences.

Entrainment Theories
Assumptions: Learning is grounded in physical enactment as opposed to information processing.
Hypotheses: The temporal structure of bodily movements organizes sensory input, motor output, and learning.

if old, whether it was an object or animal categorization (source judgement). Comparison of encoding under exercise and non-exercise conditions revealed that simultaneous exercise led to poorer source judgement; there were no differences on familiarity judgements. These behavioral results, together with neuro-electric brain recordings, led Soga and colleagues to conclude that acute aerobic exercise compromised hippocampal processes involved in source judgment but not familiarity judgments, which rely less on hippocampal activation.

A series of experiments conducted by Lorprinzi and colleagues provide insights into the effects of exercise-induced arousal on memory storage and retrieval. Frith et al. (2017) were among the first to examine in a single experiment the impact of the temporal pairing of acute exercise and encoding on memory. Young adults were assigned to separate conditions in which they performed a bout of exercise either prior, during, or following encoding or a no-exercise control condition. Exercise consisted of a 15-min treadmill run in which the first 5 min was jogging (RPE 11–12), the next 5 min was spent running at faster pace (RPE 13–15), and the final 5 min was spent running at a hard pace (RPE 16–20). Pacing at each stage was self-selected. During encoding periods, participants listened to a list of 15 individually presented words which were presented successively 5 times (Rey Auditory Verbal Learning Test- RAVLT). Free recall memory was assessed 20-min post encoding and a recognition test of memory was taken 24-h post encoding. The recognition test consisted of the presentation of the 50 words heard during encoding and 20 new distractor words. Performance was measured in terms of recognition and list attribution. Prospective memory was quantified by a time-based procedure in which participants were asked to telephone the researcher at an agreed upon time. When measured after a 20-min delay, participants in the simultaneous encoding group and the control group recalled significantly fewer words than participants who exercised prior to encoding. There were no differences in participants' free recall regardless of condition when evaluated after a 24-h delay. Word recognition differed among the groups; individuals in the simultaneous encoding and post-encoding conditions performed significantly poorer than those who exercised prior to encoding. Measures of prospective memory did not differ among groups.

In a similarly designed study, Sng et al. (2018) compared long-term memory and prospective memory in groups of young adults who either rested or performed a low intensity 15-min treadmill walk prior to, during, or following encoding. Participants completed the RAVLT during encoding periods. Free recall memory was assessed 20-min post encoding and a recognition test of memory was taken 24-h post encoding. Prospective memory was measured by the Red Pen Test, which provided an index of participants' ability to remember to execute a specific response. Measured at both 20-min and 24-h delay periods, participants who simultaneously walked and encoded the word list performed significantly poorer than those who exercised before encoding. Notably, there was no significant difference between those who exercised prior to encoding and the control group. In addition, the prospective memory of participants in the simultaneous condition was significantly poorer than that of participants in either the before condition or the control condition. The lower memory performance of participants in the simultaneous condition compared to the before exercise condition was explained by Sng and colleagues as the result of competition for attentional resources (Dietrich and Audiffren, 2011).

Tomporowski et al. (2017) investigated the effects of physiological arousal produced by isometric muscle contractions on free-recall and recognition memory. Using a within-participant and counterbalanced design, young men, and women studied different 20-item word lists under four conditions: a 100-s hand-grip contraction during word encoding, consolidation, retrieval, and a no-contraction control condition. Arousal was manipulated by assigning participants to either a low-intensity (10% maximum grip strength contraction) or a moderate-intensity (50% maximum contraction) exercise group. A free-recall test was administered immediately following each trial and a comprehensive delayed free-recall test was given 5-min following the last trial. A recognition memory test was administered immediately following the delayed free-recall test. One hundred words were visually presented; 50 of the words had been presented during the test and 50 words had not been presented. The participant was asked to indicate whether an item was from one of the word lists presented earlier or whether it was a new word. Isometric exercise was not performed during either the comprehensive recall test or the recognition memory test. Statistical analyses revealed that arousal level did not differentially influence encoding. However, fewer words were recalled during immediate and delayed free-recall tests and recognition tests under conditions in which participants performed the handgrip exercise while encoding than when exercise was performed during recall, consolidation, or control conditions. The researchers surmised that dual-task costs are particularly high during the encoding phase of learning.

Summary of Arousal Theory

All studies reviewed here on the basis of hypotheses drawn from arousal theory and accompanying neuro-psychological based models consistently show evidence that a combination of exercise and encoding negatively impacts long-term declarative memory. Several experiments make clear comparisons between conditions in which exercise is performed concurrently with encoding and conditions in which exercise is performed prior to or following encoding. The evidence in these studies depicts less efficient long-term memory storage of declarative information under the former condition. Further, there is little support for an inverted-U relation between exercise intensity and memory of declarative information.

ATTENTION THEORY

The relation between attention and memory has been studied extensively for over a century (see Mulligan, 2008 for a review). Attention is typically viewed as a focusing process that plays a critical role in encoding, short-term memory, and long-term memory (see Jonides et al., 2008, for a review). The focus of attention can be placed on encoding, which is a perceptual process, as well as memories stored from past experiences. Information that is encoded and comes into the focus of attention can displace other memory contents from attentional focus. Attentional processes control what information enters into the focused state. This on-line processing explains the limited storage capacity of short-term memory. Attentional processes not only serve as "gating" mechanisms and determine what enters consciousness, but also how the information is maintained, and how additional information is retrieved from short-term and long-term memory storage. Memory performance degradation is typically explained in terms of either the decay of memory traces (engrams) in cortical structures (Loprinzi et al., 2017) or the interference among items held in perceptual memory, short-term, and long-term memory (Jonides et al., 2005). Of central importance to the present review is how concurrent physical activity may moderate the ability to overcome interference.

Attention Research: Experimental Evidence

A series of experiments examined the effects of walking on young and older adults' memory. The studies were designed to test predictions derived from the Selection, Optimization, and Compensation (SOC) theory (Baltes and Baltes, 1990; Baltes and Lindenberger, 1997), which focuses on age-related shifts in the quality of sensorimotor processing. The SOC theory posits that individuals respond to environmental challenges via selection and modification of task goals and optimization of goal-directed compensatory strategies required to achieve those goals. With age-related declines in sensory acuity and proprioception, older adults are predicted to allocate increasingly more attentional resources to maintaining desirable levels of balance and walking control. Lindenberger et al. (2000) employed a dual-task methodology to assess the magnitude of dual-task interference between memorization of words and walking. 47 young (ages 20–30 years), 45 middle-aged (40–50), and 48 old (60–70) adults were trained to walk quickly and accurately on narrow paths that differed in movement complexity. In separate sessions, participants encoded 16 words presented auditorily while sitting, standing, or walking for 2.8 min on either track. Immediate serial recall tests were administered. Recall performance in the context of walking was lower than recall performance in the context of seated and standing conditions. Middle- and older-age participants showed a 22% loss in serial recall under a simple walk condition and a 36% loss during the complex walk whereas young adults showed no loss following the simple walk and a 19% loss during the complex walk. Similar findings were obtained from a subsequent study (Li et al., 2001) which retained the methods employed by Lindenberger et al. (2000) but individualized the walking and memory demands for each participant. Compared to a seated condition, older adults (60–75 year) showed significantly poorer serial recall performance following walking than did young adults (20–30 year). Younger adults showed no dual-task interference effect when performing a simple walk condition, and interference only when the walking task was more challenging (e.g., path obstacles).

A series of experiments conducted by Helton and colleagues focused on dual-task challenges presented in naturalistic conditions. In one study (Epling et al., 2016), young adults were asked to remember 20 words presented auditorily at 15-s intervals during a vigorous 5-min run on an outdoor running track. Immediately following the run, participants completed a 90-s written word-recall test. Significantly fewer words were recalled following the run than when the participant encoded words while seated. Similar results were obtained in two studies that evaluated dual-task interference when encoding words while performing traverse wall climbing (bouldering). Green and Helton (2011) assessed dual-task costs of bouldering across a climbing wall for three minutes and encoding 20 words presented auditorily every 8 s with a 14-s pause after the final word. Immediately following the climb, participants completed a 90-s written word-recall test. Compared to a single-task condition in which encoding occurred while seated, the dual-task condition resulted in a 50% decrease in recall performance. In a replication study, Darling and Helton (2014) presented words with irregular timing and the duration of traverse climbing was increased to 5 min. Compared to word recall performance in a single non-exercise condition, participants recalled nearly 40% fewer words. Results of these two studies suggested to the researchers that effortful processing required to traverse the wall climb interfered with the rehearsal and maintenance of words to be recalled.

Summary of Attentional Allocation Research

All studies reviewed here that were conducted on the basis of hypotheses drawn from attention theories consistently show evidence of CMI that negatively impacted the encoding of declarative information into long-term memory. The magnitude of interference appears to be age-related, with middle-age, and older adults showing less effective word memorization than younger adults. The data suggest that dual-task conditions that require motor movement planning and corrections compete with the ability to retrieve strategies from memory storage that are required for processing cognitive tasks, and thus negatively affect the encoding of semantic information into long-term memory storage.

COGNITIVE-ENERGETIC THEORY

Proponents of cognitive-energetic theories suggest that traditional information-processing models that view processing systems as operating in a computer-like, mechanical, "dry" fashion are insufficient because they fail to acknowledge the importance of "wet" biological and motivational systems that underlie top-down control of behavioral output (Koelega, 1996). These theories draw from long held assumptions concerning an interrelation between top-down cognitive control and bottom up sensory input and processing (Kahneman, 1973; James, 1981/1890; Hockey, 1996, 1997; Sanders, 1997; Audiffren, 2009). Central to the early theoretical conceptualization of attention was the assumption that it guides behavior via the allocation of mental resources. Further, the amount of attentional resources available for an individual was believed to be fixed. As a consequence, attentional capacity is allocated in ways that optimize behavioral actions and their consequences when an individual is faced with performing two or more tasks at the same time (Kahneman and Treisman, 1984). While there is theoretical debate concerning whether a single central reservoir of attention or multiple reservoirs exists (Wickens, 1984, 2008), predictions concerning dual-task demands on performance are similar – when two or more tasks compete for available attentional resources, the resulting condition has the potential to lead to decrements in performance in one task in favor of the other(s).

While several contemporary cognitive-energetic theories address factors that explain dual-task performance (Dietrich and Audiffren, 2011), Cognitive Load theory (Paas and Sweller, 2012) is particularly relevant to the present review. The theory makes specific hypotheses concerning the bidirectional relation between working memory and long-term memory stores. The theory posits that the limited operational capacity of working memory is offset by the availability of schemas stored in long-term memory. Further, the primary role of working memory is to assess on-line processing of sensory experiences and to determine if they are unique, novel, and merit encoding. As schemas are hypothesized to consist of multiple elements of information that are reduced into a single element, they provide the means to overcome the computational limitations of working memory. Drawing on an evolutionary theory of human cognitive architecture (Geary, 2006), Paas and Ayres (2014) suggest that schemas that control motor movements take precedence over schemas that organize and refine the acquisition of cultural knowledge (e.g., semantic information). Paas and Sweller (2012) suggest that primary motor schemas can be used to leverage the encoding of secondary, academic material. Environmental and instructional conditions that reduce cognitive load on working memory are hypothesized to facilitate encoding and learning (Choi and van Merrienboer, 2014).

Cognitive Load Theory: Empirical Evidence

Educationally-oriented researchers have particular interests in interventions that can enhance children's memory and learning. A recent series of studies conducted with children addressed the impact of dual-task instruction on long-term memory. A study conducted by Toumpaniari et al. (2015) provided the rationale and methodology employed in several experiments. Pre-school boys and girls were taught a foreign language vocabulary via the pairing of Greek and English animal words. When presented an animal word, groups of children either physically moved and imitated animals (integrated movement), remained seated and gestured animal movements, or remained seated and verbally repeated the words. Twenty word pairings were practiced 1 h per day, 2 sessions per week for 4 weeks. The results of an immediate cued-recall test administered following the last encoding session revealed that children who were physically active and imitated animal actions recalled significantly more words than children in the gesture-only condition. Children in both physical activity and gesture groups remembered more words than children in the traditional verbal-repetition group. These results were replicated in a cluster randomized control experiment conducted with 104 elementary-age children (Schmidt et al., 2019). Groups of children between 8 to 10 years of age were instructed to associate 20 foreign animal words with 20 known animal words during four, 10-min teaching sessions that were distributed over 2 weeks. Word pairs were presented auditorily and pictorially to children who repeated the word pairs while either enacting the movements of the animal, running in place, or seated a desk. A cued-recall test administered following the final training session revealed that word recall was greater for children who were physically active during encoding than for children who were inactive. Further, the greatest memory gains were shown by children who enacted animals' actions.

These findings were supported by a series of experiments that focused on words acquired during geography, science, and mathematics instruction. In the first study Mavilidi et al. (2016), children ranging between 4 and 5 years of age participated in classroom lessons designed to associate animals' names with specific global continents. A large map of the globe was placed on the floor. Children paired an animal's name to a location on the map in one of three ways: physical movement that imitated the animals' "travel" to a geographical location (integrated condition); picking up an animal doll and running in a circle around the map (physical activity condition); or visually locating the animal's place on the map (control). Encoding training was conducted in three, 10-min periods over 2 days. Cued recall tests were administered immediately following the second learning day and again after 5 weeks. Children who learned under the integrated condition and the physical activity condition recalled more words than children under the control condition on both immediate and delayed memory tests. Word recall in the integrated learning and the physical activity learning groups did not differ. Similar results were obtained in cluster randomized experiment in which preschool children participated in a science lesson that involved learning the names and positions of planets in the solar system (Mavilidi et al., 2017). The sun and drawings of named planets were displayed in order on a straight line in the solar system task. During 10-min sessions conducted once per week for 4 weeks, children in the integrated instructional group ran from the center (the sun) to a planet indicated by the teacher and then back to the center, continuing for each planet. Children in the run condition were instructed to run around the solar system for several minutes and then sit and listen to the teacher name the planets. Children in the control group remained seated and listened to the teacher. Instruction was provided once each week for 4 weeks. Free-recall and cued-recall tests were administered immediately after the final practice session and again after 6 weeks. An analysis of scores combined from the two test sessions revealed that children in the integrated condition group performed better than those children in the nonintegrated (run) and control condition groups. Further, children in the "run" condition group performed better than those children in the control condition group. Another cluster randomized control trial conducted with preschool age children (Mavilidi et al., 2018a) focused on numeracy skills. One hundred and twenty preschool students received practiced counting skills during four weekly 15-min sessions. Children were assigned to one of four conditions: an integrated physical activity in which they ran, jumped, and stepped along a number line while counting; a non-relevant physical activity in which they ran around the room for 1 min; a condition during which an observer watched the students perform the integrated movements, or a seated control condition. Children's numeracy skills were assessed immediately after training and 6 weeks following the intervention. Children in the integrated, task-relevant performed significantly better than children in all other conditions.

Cognitive-Energetics Theories: Summary

Experiments that integrate children's gross motor movements into problem solving tasks performed in classroom setting consistently report improvements in the encoding of semantic information. Unlike laboratory studies, children engaged in learning sessions distributed across several days. Further, instructional environments were purposely designed to link physical activity to the creation of mental representations (e.g., schemas). As predicted by proponents of cognitive load theory, physical movements may provide leverage for encoding and remembering academic information. Planned physical actions result in sensorimotor feedback that is processed and embellished via memories of past experiences and enhance memory trace strength.

ENTRAINMENT AND EMBODIED LEARNING THEORIES

Physical activity leads to widespread biological changes that are rhythmical in nature (e.g., cardiorespiratory rate, relative timing of muscle activation, and brain activity). The importance of genetically ingrained motor movement programs and their role in encoding and storage of semantic information is central to proponents of entrainment theory. Entrainment theory builds on the dynamic nature of human movement and the temporal locking between an individual's motions with the frequency of another external rhythm (Thaut et al., 2005; Thaut et al., 2015). The phenomenon is exemplified by the linkage between the auditory rhythms embedded in music and the regulation of spatiotemporal and force parameters of movement (e.g., sway or groove). Proponents of Dynamic Attending Theory (Jones and Boltz, 1989; Large and Jones, 1999) hypothesize that the temporal structure of movements provides an endogenous template for information encoding. Rhythmic sensory inputs during movement phases are theorized to be linked to the peaks of oscillating attentional phases. The timing of specific motor movement phases (e.g., walking, running, or cycling) and accompanying peaks of oscillatory attention provides optimal conditions for encoding. Thus, learning would be predicted to be facilitated when the presentation of information to be learned (e.g., word list items) occurs in phase with periods of peak attention. Alternatively, as the out-of-phase timing between movement and encoding increases, learning is compromised. These predictions are supported by recent neurophysiological studies that have mapped direct paths and indirect paths of connectivity between networks that comprise executive functions and the hippocampi (Eichenbaum, 2017). These predictions dovetail with those of embodied learning theories proposing that learning emerges from a dynamical interaction among an individual's body movements, the sensory experiences obtained from the movements, and the context of those movements (Newell, 1986; Lindgren and Johnson-Glenberg, 2013). As individuals navigate through complex environments and perform actions, a framework is developed that allows them to learn about the world and how actions provide the means to achieve goals. Memory of movements is thought to be retained in real time and depends on the sensory and motor experiences obtained during physical actions. Learning is hypothesized to be grounded in enactment, in which memories are encoding through sensory experiences derived from such physical actions as gestures, walking, and play (Lindgren and Johnson-Glenberg, 2013; Gallagher and Lindgren, 2015). The movements that occur during enactment are hypothesized to engage not only the motor system but also to facilitate the construction of mental representations that enhance memory recall (Moreau and Tomporowski, 2018).

Entrainment Research: Experimental Evidence

A series of studies conducted by Schmidt-Kassow and colleagues provide support for the beneficial role of entrainment on memory storage. Young women in one experiment participated in two identical laboratory sessions in which separate groups of participants rested or cycled on an ergometer at a low-to-moderate intensity for 30 min either prior to or during encoding auditorily presented word lists (Schmidt-Kassow et al., 2013). Individual words were presented every 2 and 6 s and corresponded to the 60-RPM cycling cadence maintained by the participant. This manipulation was based on prior research demonstrating the temporal predictability benefits of acoustic stimuli (Schmidt-Kassow et al., 2010; Schmidt-Kassow et al., 2017). Cued-recall tests were administered 48 h following encoding. Significantly more words were recalled in both sessions when encoding occurred simultaneously with cycling exercise than when a rest period preceded encoding. Word recall performance of participants who exercised prior to encoding did not differ from that of participants in either the simultaneous or rest conditions.

A subsequent study provided additional support for the benefits of pairing acute physical activity with encoding (Schmidt-Kassow et al., 2014). In two separate experiments, young men, and women completed two sessions during which they either encoded a list of words while treadmill walking or remained seated. Each participant was provided treadmill familiarization training and his or her preferred walking speed was identified. The participants' walking speed was synchronized to the presentation of individual words. A paired-association paradigm was employed in which 40 Polish-German words were paired. One word of each pair was presented every fourth step. Participants verbally repeated the word pairs during an 8.2 s (12-step) separation between word pairs. The word-pair list was presented twice during the 30-min treadmill walk. In both experiments, cued-recall tests were administered 24 h after each session. The only methodological difference between the experiments was blood draws that yielded separate evaluations of the kinetics of brain-derived neurotropic factor (BDNF) and cortisol. The behavioral data were consistent across both experiments, with superior word recall occurring following concurrent exercise-encoding sessions compared to non-exercise conditions. The research conducted by Schmidt-Kassow and colleagues highlight the fact that subtle differences in the synchronization of movement with word presentation can exert substantial effects on long-term memory.

Summary of Entrainment Research

While limited in number, the studies designed on the basis of hypotheses drawn from entrainment theory consistently provide evidence of long-term memory facilitation. As predicted, gains in long-term memory were observed following the coupling of locomotor movements with word presentation. Central to the methods employed in these studies is the precise timing of the presentation of words to be remembered with cycling cadence and with self-paced walking. As predicted by proponents of entrainment theory and embodied learning theory, memory storage may reflect the results of a dynamic interplay among environmental information, task constraints, and organism constraints. Central to embodied learning theory is an assumption that muscle coordination, control, and skill emerge as self-organizing coordinative structures through the unity of perception and action.

DISCUSSION

The pairing of physical activity with cognitive task performance constitutes a dual-task condition and the potential for CMI. The manner in which interference affects cognitive performance or movement performance depends on several factors. The goal of the review was to use contemporary cognitive theory to search for consistent themes that explain outcomes from learning conditions that combine motor movements with the encoding of semantic information. The rationale for the review was based on evidence showing the multicomponent training conditions that pair physical activity with mentally engaging tasks result in higher gains in cognitive performance than when physical activity is performed in isolation (Tomporowski and Pesce, 2019). Further, educators, mental health practitioners, and gerontologists have considered the merits of physical activity interventions designed to enhance or maintain cognitive functions. As such, we were particularly interested in dual-task studies that lead to long-term improvements in learning.

While relatively few experiments have been conducted that study the phenomenon, the results of the 16 studies evaluated here provide some resolution concerning specific dual-task conditions and their outcomes. As predicted by the CMI task classification system developed by Plummer et al. (2013), some of the studies led to impaired memory storage while others provided evidence of memory enhancement. Dual-task studies resulting in degraded long-term memory performance measured semantic memory following encoding that occurred while walking on pre-arranged pathways that included obstacles (Lindenberger et al., 2000; Li et al., 2001), engaging in speeded traverse wall climbing (Green and Helton, 2011; Darling and Helton, 2014), maintaining specific levels of muscular exertion (Tomporowski et al., 2017), and cycling or running at paced speeds (Epling et al., 2016). Studies finding improvements in long-term semantic memory measured young children's learning in immersive classroom activities that involved running while acquiring vocabulary words (Toumpaniari et al., 2015; Schmidt et al., 2019), animal names (Mavilidi et al., 2016), planet names (Mavilidi et al., 2017), and numeracy (Mavilidi et al., 2018a). Similarly, young adults' memory of words was found to be greater when words were presented in synchrony with ergometer cycling pacing (Schmidt-Kassow et al., 2013) and self-paced treadmill walking (Schmidt-Kassow et al., 2014).

Contemporary theoretical views of arousal, attention, working memory, and memory storage are central to explaining the differences among these studies. Attentional focus is thought to determine the entry of information into short-term working memory where the capacity limitations of short-term memory are considered crucial for establishing long-term memories (Jonides et al., 2008; Paas and Ayres, 2014). Executive functions are central to the planning, selection, and guidance of movements (Diamond, 2013). Further, the proprioceptive feedback that occurs during movements and evaluation of the consequences of actions are interpreted by executive functions (Schmidt, 1975). Based on capacity theories of attention, it would be expected that the processing required to control motor movements and update sensory feedback would compete for available computational resources. From these theoretical perspectives, declines in semantic encoding would be predicted.

Explaining improvements in semantic memory storage under dual-task conditions that include motor movement presents a challenge for traditional attention theories. One method of identifying factors that contribute to improved learning under dual-task conditions is to rule out possible explanations. For instance, experiments that examine the role of automaticity on dual-task costs (Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977) report results suggesting that protracted practice on one task leads to less top-down processing and reduction in working memory requirements. However, none of the studies reviewed here reporting memory enhancement included extensive motor-movement training. Alternatively, data obtained from memory research suggests that emotionally laden events that evoke intense physiological stress responses provide the basis for flashbulb memories, which are vivid and may be stored virtually indefinitely in episodic long-term memory (Hirst and Phelps, 2016). Episodic memories are considered to be a type of declarative memory that is unique to an individual and reflects personal experiences (Squire and Wixted, 2011). Many individuals can recall in great detail experiences encoded during intense sport training and competition. Such observations have led researchers to conclude that high-intensity exercise may provide conditions that enhance the encoding of events that occur prior to, during, and following intense, stressful bouts of physical activity (Lucas et al., 2015). As described previously, research conducted on stressors that elicit fear patterns in animals (e.g., startled response and freezing) heighten episodic and spatial learning (McGaugh, 2018). These changes in learning are explained in terms of limbic-based structures and networks that involve the amygdala and hippocampus and signal widespread homeostatic responses and regulation. However, none of the dual-task experiments evaluated in the present review employed the levels of intense physical activity that might lead to stress levels that elicit strong emotional responses. Further, a recent meta-analysis found little difference between the effects of acute bouts of moderate or intense exercise on cognitive function (Moreau and Chou, 2019).

The dual-task studies that led to improved semantic memory are characterized by game-like play, self-paced movement, and the manner by which information to be learned was timed with physical movement. The finding that game-like academic learning that involves the pairing of physical activity with encoding of words is in line with positions held by researchers who have proposed the importance of the qualitative aspects of chronic physical activity interventions. The value of physical activities that are meaningful, goal-directed, and pleasurable are hypothesized to enhance execute functions (Diamond and Ling, 2016; Tomporowski and Pesce, 2019). The beneficial effects of game-like activities on children's memory also support predictions concerning the interactive role of cool and hot executive networks (Zelazo and Carlson, 2012). The affective responses individuals derive from physical movements while immersed in goal-directed learning may alter motivation and level of engagement (Stych and Parfitt, 2011; Vazou and Smiley-Oyen, 2014; Vazou and Skrade, 2017). The neural connectivity between structures of the pre-frontal cortex and the hippocampus has been described recently and may help explain how low-to-moderate levels of mentally engaging exercise paired with goal-directed behavior might provide the basis for enhanced memory storage (Eichenbaum, 2017).

Neurobiological research provides evidence of direct and indirect connections between the prefrontal cortex and the hippocampus and that memory storage is mediated by oscillatory synchrony of neural activity (Eichenbaum, 2017). The finding that the timing between movements and memory encoding enhances memory supports predictions made by Dynamic Attending theory (Large and Jones, 1999), which emphasizes the role of the timing of biological rhythms inherent in movement with sensory experiences derived from motor actions. Self-paced treadmill walking has been shown to improve children's (Schaefer et al., 2010) and older adults' (Tomporowski and Audiffren, 2014) executive processing. On the basis of entrainment theory, participants in these studies may have adjusted their walking pace to synchronize movements with the timing of information entering working memory. Treadmill walking and highly practiced motor skills are often assumed to be highly reflexive and require limited attentional control (Regnaux et al., 2006). However, attempts to alter or modify ingrained actions require effortful attention processing that competes for mental resources that could be allocated to other tasks (Beilock et al., 2002). It is plausible that dual task conditions that minimize top-down motor movement control lead to improvements in declarative learning by providing additional working memory space.

CONCLUSION

The results obtained from 16 experiments suggest that declarative memory can be enhanced under specific dual-task conditions. However, several caveats are in order. The experiments selected for review were not derived from a systematic literature search. The studies were linked to four overlapping categories of theories: arousal, attention, cognitive-energetic, and entrainment theory. Our theory-based approach was designed specifically to target dual-task experiments that examined memory and learning outcomes. The intent was to identify conditions that create cognition-motor interference but benefit declarative memory. As predicted, the differences observed in the outcomes of studies reviewed are related to subtle methodological factors. For example, the relation between exercise and memory may be due to the timing of memory testing. Roig et al. (2016) highlighted the importance of delayed tests of long-term memory. Memory testing conducted immediately or soon after encoding in their research provided negligible learning. However, testing conducted 24 h and 7 days following encoding provided unambiguous evidence of the effects of acute exercise on procedural learning. It is noteworthy that 8 of the 16 studies reviewed included memory tests administered 24 h or longer after the learning phase and that 6 of the 8 experiments support the provision of sufficient time for the consolidation of long-term memory.

Further, there is a general consensus that there are several different types of memory; e.g., perceptual, procedural, episodic, semantic, and spatial (Schneider, 2015). Advances in technology and neuroscience have led to a better understanding of brain structures and functions that help explain how human experiences lead to the organization and re-organization of knowledge. While considerable advances in understanding the linkages between physical activity and memory have been made recently, attempts to explain the relationship will benefit from a wider selection of tests of memory than those currently populating the literature. Soga et al.'s (2017) experiment exemplifies the strength of evaluating multiple types of memory and identifying dissociations in outcomes that conform to theoretical predictions. At a more elementary level, it will also be informative to examine closely the information-processing characteristic of memory tasks selected for experimentation. Many of the 16 studies reviewed that failed to observe memory benefits employed tests that presented to-be-remembered items at a relatively fast rate. Most of the experiments that observed beneficial effects either paced the presentation of words with movements (e.g., Schmidt-Kassow et al., 2014) or provided considerable delays between items to be remembered (e.g., Toumpaniari et al., 2015; Mavilidi et al., 2017). Additional research focused on the timing of motor movement and rate of presentation of information to be encoded may address theoretical questions concerning the role of central (e.g., Kahneman, 1973) or distributed (e.g., Wickens, 1991) attentional resources, as well as the clinical applications of dual-tasking interventions. Regardless, research that looks closely at the type and the characteristics of memory tasks will be useful for theory development and subsequent applications to multiple populations.

Developmental and aging factors are also of particular importance. Five studies performed in educational settings demonstrated children's retention of academic information. However, children in these experiments engaged in several dual-task training sessions that were distributed over several weeks. These studies differ from traditional acute dual-task training experiments, which are limited to assessing the effects of a single exercise bout. While they might be considered to be chronic exercise interventions, the total memory encoding durations were similar to those of single session experiments. Additional studies that track the strength of memory encoding over multiple training sessions are needed. It is unknown if the game-like conditions experienced by children have similar effects on adolescents' and adults' learning.

There is considerable interest in determining whether school lessons that include physical activity will boost children's academic progress (Vazou and Smiley-Oyen, 2014; Donnelly et al., 2016; Daly-Smith et al., 2018; Mavilidi et al., 2018b) and whether multi-component activities help older adults offset or reverse age-related changes in cognition (Tomporowski and Pesce, 2019). Clearly, additional theory-based research is needed that provides guidance concerning the application of physical activity interventions designed to enhance cognition. Theory-based literature reviews geared toward explaining the relationship between exercise and cognition provided added value to traditional meta-analytic reviews that describe and quantify the strength of the relations that exist between exercise and cognition.

AUTHOR CONTRIBUTIONS

PT performed the literature search. PT and AQ drafted the manuscript, and both authors approved the final version of the manuscript.

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Skill Acquisition Methods Fostering Physical Literacy in Early-Physical Education (SAMPLE-PE): Rationale and Study Protocol for a Cluster Randomized Controlled Trial in 5–6-Year-Old Children From Deprived Areas of North West England

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Background: There is a need for interdisciplinary research to better understand how pedagogical approaches in primary physical education (PE) can support the linked development of physical, cognitive and affective aspects of physical literacy and physical activity behaviors in young children living in deprived areas. The *Skill Acquisition Methods fostering Physical Literacy in Early-Physical Education (SAMPLE-PE)* study aims to examine the efficacy of two different pedagogies for PE, underpinned by theories of motor learning, to foster physical literacy.

Methods: SAMPLE-PE will be evaluated through a cluster-randomized controlled trial targeting 5–6 year old children from schools located in areas of high deprivation in Merseyside, North-West England. Schools will be randomly allocated to one of three conditions: *Linear Pedagogy*, *Non-linear Pedagogy,* or Control. Non-linear and Linear Pedagogy intervention primary schools will receive a PE curriculum delivered by trained coaches over 15 weeks, while control schools will follow their usual practice. Data will be collected at baseline (T0), immediately post-intervention (T1), and 6 months after the intervention has finished (T2). Children's movement competence is the primary outcome in this trial. Secondary outcomes include physical activity, perceived competence, motivation, executive functions, and self-regulation. An extensive process evaluation will also examine implementation factors such as intervention context, reach, dose, fidelity and acceptability.

Discussion: The SAMPLE-PE project will enable better understanding surrounding how to operationalise physical literacy through enrichment of PE practices in early PE. The study will provide robust scientific evidence regarding the efficacy of underpinning PE pedagogy with theories of motor learning to promote the development of physical literacy.

Trial Registration: Retrospectively registered on 5th September 2018 at ClinicalTrials.gov, a resource provided by the U.S. National Library of Medicine (Identifier: NCT03551366).

Keywords: movement competence, low socioeconomic status, executive function, self-regulation, intervention, motor learning, pedagogy, mixed methods

INTRODUCTION

Physical Literacy and Physical Education

Physical literacy can be understood as the embodied relationship between a child's movement competence (physical), motivation and confidence (affective), knowledge and understanding (cognitive), and also their environment, which shapes movement and ongoing physical activity behaviors (Whitehead, 2010; Cairney et al., 2019). Across the globe, primary school PE curriculums, national standards and policies reference the support of the whole child, including physical, affective, cognitive and social development (The Australian Curriculum Assessment and Reporting Authority, 2012; Department for Education, 2013; United Nations Educational, Scientifc and Culture Organisation, 2015) thereby advocating the importance of physical literacy (Shape America, 2013; Sport England, 2013; Tremblay et al., 2018). It is widely accepted that early quality PE experiences are crucial for laying a strong foundation to support children on their physical literacy journey (Whitehead, 2010; Dudley, 2015). Nevertheless, there is a need for interdisciplinary research into physical literacy to better understand how pedagogical practices can foster physical literacy in early primary school.

Supporting Physical Literacy Through Movement Competence

Although physical literacy is considered a holisitic concept with relevance through the life course, the early to middle childhood period is particularly important for nurturing the development and acquisition of foundational movement skills (e.g., running, jumping, catching, kicking) and abilities (e.g., agility, balance, coordination) (Whitehead, 2010; Giblin et al., 2014; Hulteen et al., 2018) collectively known as movement competence. Movement competence exists across a spectrum of human movement and is dependent upon an individual's capacity to control, coordinate and perform movement skills efficiently (movement proficiency), as well as to adapt, attune and combine movement skills, creating novel functional solutions (movement creativity) across a broad range of physical activity and sporting contexts (Orth et al., 2017; Bardid and Utesch, 2018; Ng and Button, 2018). The ability to efficiently and functionally adapt, combine and execute movement skills requires emotional regulation, perceptual skills and a high degree of knowledge and understanding of the task at hand; the process of learning foundational movement skills will therefore drive the emergence of all aspects physical literacy in children (Rudd et al., 2016). Thus, supporting movement competence is considered central to fostering meaningful experiences in PE (Beni et al., 2017) therefore nurturing the physical literacy journey (Roberts et al., 2019b).

Low levels of movement competence have been reported among 4–8 year old primary school-aged children in western countries (Bardid et al., 2015; Foulkes et al., 2015; Morley et al., 2015). In particular, children from areas of relatively high deprivation in England (as calculated using the home postcode and information from domains including income, employment, education, health, crime, barriers to housing and services, as well as the living environment: see English indices of deprivation; Ministry of Housing Communities Local Government, 2018) have less developed movement skills than their peers from more affluent areas (Foulkes et al., 2015; Morley et al., 2015; Barnett et al., 2016). Children living in more deprived areas may require targeted movement competence interventions in PE due to a lack of opportunities to take part in physical activity outside of school or safe outdoor spaces within their community (Foulkes et al., 2015; Morley et al., 2015; Barnett et al., 2016). Low movement competency among more deprived children is a concern because children with low levels of movement competence have lower cardiorespiratory fitness, and are more likely to be overweight or obese, compared to children who perform these skills well (Lubans et al., 2010; D' Hondt et al., 2014; McWhannell et al., 2018). From an affective perspective, children with high movement competence have been found to

Abbreviations: EUPEA, European Physical Education Association; NIH, National Institutes for Health; OECD, Organisation for Economic Co-operation and Development; PE, Physical Education; RCS, Response to Challenge Scale; RCT, Randomized Controlled Trial; SAMPLE-PE, Skill Acquisition Methods fostering Physical Literacy in Early – Physical Education; SDQ, Strengths and Difficulties Questionnaire; STEP, Space, Task, Equipment, People; TGMD-3, Test of Gross Motor Development Third Edition; UNESCO, United Nations Educational, Scientific and Cultural Organization.

have higher perceived competence (Barnett et al., 2011; Liong et al., 2015; Duncan et al., 2018) which is important because children who feel confident whilst participating in PE are more likely to enjoy involvement, and consequently feel intrinsically motivated to continue effort and participation in all forms of physical activity. From a cognitive perspective, the ability to perform complex movement skills is positively associated with higher-order cognitive skills, i.e., core executive functions: working memory, inhibitory control and cognitive flexibility (Van Der Fels et al., 2015; Oppici et al., 2020), that allow children to manage their thoughts, actions and emotions in order to accomplish everyday tasks, and also to plan, organize and manage their time effectively. The development of complex movement skills through well-designed PE lessons can act as a 'carrier' of higher-order cognitive skill learning beyond those achieved through traditional classroom-based activities (Mavilidi et al., 2018). Behaviorally, children with higher levels of movement competence are more likely to be physically active during childhood, which in turn tracks into adolescence (Foweather et al., 2014; Holfelder and Schott, 2014; Lai et al., 2014; Cohen et al., 2015), determining positive trajectories of health (Robinson et al., 2015). In sum, poor movement coordination development among children living in areas of high deprivation may have wide-reaching adverse effects on their perceptual skills, cognition, social and emotional development and health (Leonard and Hill, 2014; Libertus and Hauf, 2017). Early intervention is seen as crucial given that an increasing proportion of young children have poor movement competence (Bardid et al., 2015; Foulkes et al., 2015; Morley et al., 2015). Whilst these articles highlight the potential benefits of movement competence, much of the research to date is cross-sectional or longitudinal (Holfelder and Schott, 2014; Robinson et al., 2015). There is a need for more experimental research within PE to provide robust evidence for movement competence influencing not only physical, but also cognitive and socio-emotional aspects of physical literacy (Whitehead, 2010; Dudley, 2015; Cairney et al., 2019).

Use of Pedagogy in Movement Competence Interventions

In order for children living in deprived areas to develop high movement competence, it is important that they can access a PE curriculum with a strong theoretical basis, delivered by skilled practitioners, using systematic, progressive and developmentally-appropriate approaches to learning (Sweeting and Rink, 1999; European Physical Education, 2009). There have been a number of PE-based curriculum intervention studies which have focused on early primary school children's development of foundational movement skills such as object-control (e.g., catching, throwing, kicking) and locomotor (e.g., running, hopping, jumping) skills (Robinson et al., 2015; Tompsett et al., 2017). While, in general, these interventions were successful, there is no clear indication in terms of the most effective pedagogy, curriculum, teaching behaviors and/or instructional strategies (Morgan et al., 2013; Robinson et al., 2015; Beni et al., 2017; Tompsett et al., 2017; Wick et al., 2017). Research in motor learning and control has advanced our knowledge about the physical, perceptual and cognitive processes involved in the learning of movement (Chow et al., 2016; Schmidt, 2019). These theoretical approaches can be used to inform the design of optimal learning environments to develop movement competence and support more broadly, physical literacy within primary school PE.

Linear Pedagogy

A popular pedagogical approach for teaching PE in young children is the Direct Instruction Model (Metzler, 2017). The main aim of this pedagogical model is to create 'closed' environments that are highly structured, and overly constrained environments that first develop content (i.e., 'technical proficiency') before being applied to various contexts (i.e., within the 'open' environment of a game or performance setting) (Blomqvist et al., 2001; Kirk, 2010). This pedagogical model aligns with cognitive and linear approaches to motor learning in accordance with Information Processing Theory (Kirk et al., 2006; Ennis, 2017; Schmidt, 2019). Lesson design structure and teaching methods hold with the premise that learning (movement) is a gradual linear process where the development of a skill progresses through main observable stages of learning (cognitive, associative, and autonomous) characterized by a reduction in cognitive processing when performing the movement skill (Fitts and Posner, 1973). This linear pedagogy includes both prescriptive (e.g., following technical demonstrations and instructions from the teacher) and repetitive actions (e.g., repetition targeting the replication of the optimal technique), where variability is reduced until a performer can execute a movement skill efficiently and reliably (Schmidt, 2019). Feedback is largely a one-way process from the teacher to the child for error detection and correction.

To fully appreciate the potential of these linear pedagogical curriculums to foster physical literacy in children, it is important to consider the individual learning experience. Children's perceptions of competence and motivation may be influenced through emphasis and development of movement proficiency in one optimal technique and may result in a sense of mastery over the skill, leading to early feelings of success that should increase perceptions of competence, contributing to higher levels of motivation in the lesson (Ryan and Deci, 2000, 2017). From a cognitive perspective, it is suggested that pedagogies that follow a linear progression of skill learning may support the natural scaffolding of executive functions as inhibitory control and working memory, providing the architecture for cognitive flexibility to be built upon (Deák and Wiseheart, 2015; Van Der Fels et al., 2015; Pesce et al., 2016a). This is due to the learning design of Linear Pedagogy first constraining children to practice skills in isolated environments before moving into a game or performance situation that will require cognitive flexibility. Evidence suggests that PE interventions aligned to the Direct Instruction Model and/or reflecting linear methods of skill learning are an effective teaching strategy for supporting young children to develop movement skill proficiency (Morgan et al., 2013; Tompsett et al., 2017; Wick et al., 2017). However, some of this evidence can be interpreted as low-quality, while many studies lack long-term follow-up (Morgan et al., 2013; Wick et al., 2017). Further, while studies have documented increases in movemennt skill proficiency, there is a lack of evidence for movement creativity outcomes, and limited evidence of concomitant increases in affective and cognitive domains, as well as physical activity behavior (Morgan et al., 2013; Lai et al., 2014; Tompsett et al., 2017).

Non-linear Pedagogy

The theory of Ecological Dynamics, offers a Non-linear perspective on the learning and development of movement skill (Chow et al., 2007). According to Ecological Dynamics, goal-directed movements are the product of the interaction between personal, environmental and task constraints (Chow et al., 2011). From this perspective, motor learning is not simply a matter of processing information and accruing representations (as is the case in cognitive theories) (Bailey and Pickard, 2010). Learners are regarded as complex adaptive systems who are presented with opportunities for action (affordances) from their environment. The concept of affordances highlights the interaction between the environmental features and functional capabilities of the individual child. Children are able to identify affordances within their environment based on their level of movement development (Newell, 1986). Newell (1986) also proposed three observable stages of learning coordination, control and skill. At an unconscious level, the learner is solving the degrees of freedom problem in early skill learning through freezing out or locking joints and body segments, allowing them to achieve the movement goal in a rudimentary form. As they move through the stages of learning will see an unlocking of degrees of freedom eventually in the skill stage learners are able to exploit environmental features to enhance and execute goal-directed movements in an energy-efficient manner that appears almost effortless. In Non-linear Pedagogy, the teacher's role is to design learning experiences in which the child's capability and environmental opportunities are closely aligned, creating opportunities for goal-directed movement (i.e., affordances). One way for the teacher to create affordances and channel the child's movement competence development is through manipulation of task and environmental constraints (e.g., rules, space, equipment). This manipulation aims to promote an external focus of attention that limits the allocation of resources to motor coordination and control processes and facilitates the implicit learning of movement skills (Profeta and Turvey, 2018). The child is left free to experiment by performing, adapting and creating movement solutions that best answer their individual needs within a given context. Traits of non-linear pedagogy can be observed in pedagogical models such as 'Teaching Games for Understanding' and teaching styles such as inquiry-led, co-operative, and discovery learning (Mosston, 2002; Tan et al., 2012; Metzler, 2017).

A Non-linear pedagogical approach to learning in PE also has implications for a child's affective and cognitive development, and physical activity behavior. Similar to linear pedagogies, the development of movement competence may increase perceptions of competence, contributing to generally higher levels of motivation. Moreover, Non-linear Pedagogy may have specific implications for children's autonomous motivation for PE, as children are provided with choice and freedom to move in different ways within their PE lessons, which could enhance their enjoyment and perceptions of autonomy (Ryan and Deci, 2000, 2017). Further, the focus on finding different movement solutions to achieve a goal may see a shift in how the child views competence, away from an 'ideal' movement performance toward functional, creative movements (Lee et al., 2014; Moy et al., 2016). The respect the teacher or coach gives to the child's ability to explore, learn, work with others and problem solve may also enhance the child's feelings of relatedness (Ryan and Deci, 2000, 2017). A Non-linear Pedagogy may have a favorable impact on the development of executive functions as the search for different solutions of an emerging movement problem involves inhibiting routines, working with ideas in working memory and flexibly shifting between potential solutions (Pesce et al., 2016b) and the non-linear instructional environments designed by supportive instructors can elicit children's commitment and emotional investment (Diamond and Ling, 2019). From a behavioral perspective, it is suggested that the long-term effect of this pedagogy is that children could acquire a wide range of functional movement solutions that are both adaptable and attuned across a variety of physical activity environments (Renshaw et al., 2010; Chow and Atencio, 2014).

While the potential holistic benefits of Non-linear Pedagogy for primary school PE have been argued (Renshaw et al., 2010; Chow and Atencio, 2014) and discussed with reference to physical literacy (Roberts et al., 2019a) to date there is limited evidence of the utilization of Non-linear Pedagogy in primary PE and little empirical evidence in support of these claims (Tompsett et al., 2017). Some PE interventions with characteristics of Non-linear Pedagogy have targeted and demonstrated improvements in movement competence among primary school children, relative to control conditions following usual PE practice (Miller et al., 2016; Pesce et al., 2016a). Miller et al. (2016) also demonstrated increased pedometer steps (physical activity behavior) in PE following the intervention; Pesce et al. (2016b) reported that movement competence (object control skills) outcomes mediated executive function (inhibitory control) outcomes. However, the observed benefits did not extend from actual movement competence to perceived athletic skill competence (Miller et al., 2016), or from inhibition to other core executive functions (Pesce et al., 2016a). Thus, further research is required to demonstrate the efficacy of Non-linear Pedagogy in PE to promote the development of movement competence and the generalizability of outcomes to aspects of physical literacy beyond the physical domain.

Aims of the Current Study

The purpose of the SAMPLE-PE study is therefore to assess the efficacy of utilizing *Linear* and *Non-linear* pedagogy within PE to promote movement competence (proficiency and creativity) and wider cognitive and affective aspects of physical literacy in 5–6 year old children from deprived areas of North West England. The SAMPLE-PE intervention is focused on PE as an ideal setting to reach all children. SAMPLE-PE targets the early primary school PE curriculum as this is the first formal opportunity for children to participate in PE in England and young children from deprived areas in a major city in north-west England have been found to be in the greatest need of such an intervention (Foulkes et al., 2015). Specifically, the main objectives of the study are to assess the efficacy of PE pedagogies (*Linear* or *Non-linear*) delivered over 15 weeks, compared to standard PE practice, on 5- and 6- year-old children's movement competence (physical domain), perceived movement competence and self-determined motivation (affective), executive function (cognitive), self-regulation (cognitive-affective), and physical activity (behavioral). A further objective of the study is to explore the potential mediating mechanisms for any intervention effects, and in particular whether increases in movement competence mediate differential effects of Linear and Non-linear Pedagogy across other elements of physical literacy. The joint focus on executive function and self-regulation is targeted to couple the more common view on the movement competence-cognition relationship, mainly focused on 'cool' executive functions elicited under affectively neutral conditions (Van Der Fels et al., 2015) with a still under-considered view on 'hot' executive function processes performed in affectively salient contexts (Zelazo and Carlson, 2012), as those involved in self-regulation (Lakes and Hoyt, 2004; Zelazo and Carlson, 2012; Lakes et al., 2013).

Hypotheses

Based on previous literature (Morgan et al., 2013; Tompsett et al., 2017), we expect that children who participate in the *Linear* and *Non-linear* Pedagogy interventions will demonstrate greater improvements in movement competence compared to children following standard PE practice. It is also expected that children in the Non-linear Pedagogy intervention will demonstrate greater movement creativity but lower technical movement proficiency than children in the Linear Pedagogy group (Lee et al., 2014). Furthermore, children in Linear and Non-linear Pedagogy interventions will show greater gains across physical literacy elements (affective [perceived competence and motivation], cognitive [cool executive functions], cognitive-affective [self-regulation] and behavioral [physical activity]) than children in standard PE practice. Finally, it is also expected that the Non-linear Pedagogy intervention will see greater improvements in children's affective (motivation), cognitive (cool executive functions: cognitive flexibility, working memory, and inhibitory control), cognitive-affective (self-regulation) domains than the Linear Pedagogy intervention (Lee et al., 2014; Alvarez-Bueno et al., 2017; Vazou et al., 2019).

METHODS

Design

A cluster-RCT will be conducted to evaluate the efficacy of the SAMPLE-PE pedagogy interventions that aim to improve movement competence and other key aspects of children's holistic development in year 1 children (5–6 years) in 12 government-funded primary schools. The trial has received institutional research ethics committee approval (Reference 17/SPS/031), and is registered (ClinicalTrials.gov identifier: NCT03551366). A schematic overview of the intervention and evaluation components is shown in **Figure 1**, while the flow diagram of schools through the study is shown in **Figure 2**. The UK school academic calendar spans September to the middle of July. Data collection will occur over 14 months with measurements at baseline (T0, January–February, 2018) and post-intervention (T1, June–July, 2018), whilst children are in year 1 of primary school, with a follow-up planned for 6 months after the intervention has finished (T2, January–February, 2019; year 2 of primary school; 1 year post-baseline assessments). The design, conduct and reporting of this cluster RCT will adhere to the Consolidated Standards of Reporting Trials (CONSORT) guidelines for group trials (Schulz et al., 2020) and the Standard Protocol Items: Recommendations for Interventions (SPIRIT) checklist (**Supplementary File 4**) (Chan et al., 2013).

Sample Size and Statistical Power

Based on previous studies (Morgan et al., 2013), we anticipate a small to medium effect size of $d = 0.4$ for changes in movement competence. In accordance with CONSORT guidelines (Schulz et al., 2020) our power calculations were adjusted for the clustering of effects at the class level. Adjusting for clustering at class level, we used a correction factor of [1+(m-1) × ICC], with participants m per class and the intraclass correlation ICC coefficient. Assuming an average class size of about 20 participants and an ICC for movement competence of 0.16 [based on TGMD-2 data of 8 classes from 7 to 8 year-olds (Rudd et al., 2016), the correction factor is 4.04 (i.e., 1+(20-1) × 0.16) (Lubans et al., 2016)]. The power calculation to detect within-between interactions for three groups and across three time points with 90% power, α levels set at $p < 0.05$ and $r = 0.5$ suggested a minimal sample size of 54 children. The final power calculation including the correction factor indicated sample size of 218 children. Allowing for 20% dropout at each time points (Foulkes et al., 2017), the aim of this study will be to have a sample of at least 314 children.

Settings and Participants

Eligible government-funded primary schools located within a large city in North West England will be invited to participate in the study via email and telephone. Eligible schools are required to be located within an area ranked within the most deprived tertile for the English population, as measured by the 2015 English indices of deprivation index (Ministry of Housing Communities Local Government, 2018). Representatives from eligible schools will subsequently be invited to an information meeting with the research team, where they will be given an in-depth overview of the project. Signed consent will be obtained from headteachers for recruitment, data collection and potential delivery of PE by the research team. Eligible children from year 1 classes will then be invited to participate in the study via a parent/carer and child invitation pack, including information sheets, consent forms, parent and child characteristics questionnaire, child medical information form, and child assent form. Children that are not able to participate in PE (e.g., due to medical conditions) or those with profound learning disabilities and formally recognized special educational needs (e.g., behavioral issues, speech and language impairment) will be excluded from

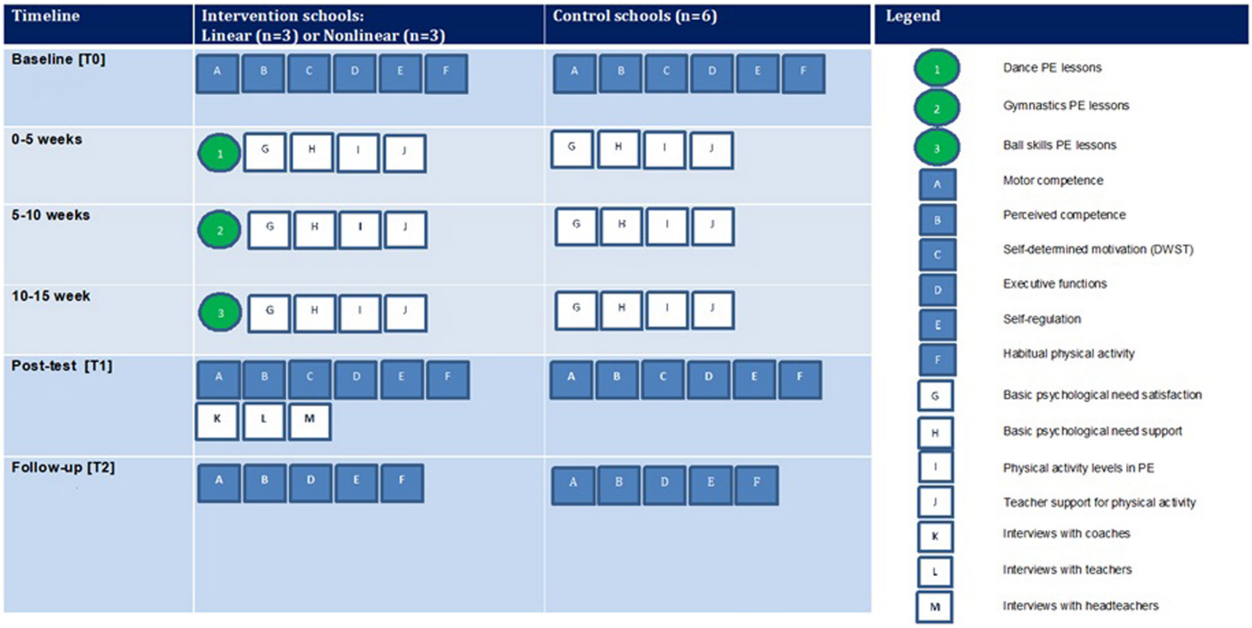

FIGURE 1 | Schematic overview of SAMPLE-PE study design and evaluation components.

assessments and data analysis. Children that do not return parent consent forms will be exempt from the research, but able to participate in PE lessons.

Blinding and Randomization

For practical reasons, it will not be possible to blind the researchers, teachers, and coaches to group allocation. Following collection of headteacher consent, randomization will take place at the school (cluster) level. Schools will then be matched based on the number of students enrolled and level of deprivation identified using the school postcode (Ministry of Housing Communities Local Government, 2018). Following this, schools will be randomly allocated to an intervention condition or control group using a computer-based random number producing algorithm by an independent researcher not associated with the study. This method ensures that schools had an equal chance of allocation to each group.

Intervention

Overview

SAMPLE-PE aims to explore the efficacy of two PE pedagogies (Non-linear Pedagogy and Linear Pedagogy), delivered through a 15-week PE curriculum in primary schools situated in areas of high deprivation. Each school being assigned to one of three conditions: Non-linear Pedagogy PE intervention, Linear Pedagogy PE intervention or control group (standard PE curriculum). All groups will have the same dose of PE (i.e., 2×60 min weekly PE lessons, for 15 weeks).

The SAMPLE-PE intervention curriculum for both the Linear Pedagogy and Non-linear Pedagogy arms will consists of 3, 5-week phases of lesson delivery commencing 2 weeks after baseline assessments. The first phase focuses on dance, the second on gymnastics and the final phase on ball sports. Each phase has its own scheme of work, which includes five lesson objectives, each taught over a two lesson period, and delivered in school during existing PE curriculum time. The lesson objectives are aligned to the aims of the English national curriculum (Department for Education, 2013) and are identical in both Linear and Non-linear Pedagogy schemes of work, but the content was differentiated by pedagogical approach in an effort to support the development of the lesson plans (described in detail below). Lessons will be delivered by trained coaches, with 45 min of on-task teaching time of the total 60 min overall lesson time, culminating in a total of 30 PE lessons.

Training Coaches for Intervention Delivery

The present study is both an efficacy and an effectiveness trial. Given that there is evidence that some generalist primary school teachers lack the confidence and competence to effectively teach PE (Morgan and Hansen, 2008), coaches will be recruited to deliver the Linear and Non-linear Pedagogy PE interventions. This approach also corresponds with current practice in primary PE in England, as the majority of primary schools currently source external providers who employ sports coaches to deliver PE (Griggs, 2016). Sport coaches will be recruited through advertisements aimed at postgraduate and undergraduate students undertaking Sports Coaching or PE courses or via the university's in-house sports coaching provider. Applicants will be shortlisted if they have a level 2 coaching qualification in any sport, meaning that they can independently plan, prepare and deliver sessions and they have basic emergency first aid, safeguarding and protecting children certificates. Further, it is desirable that coaches will have at least 1-year's coaching and/or

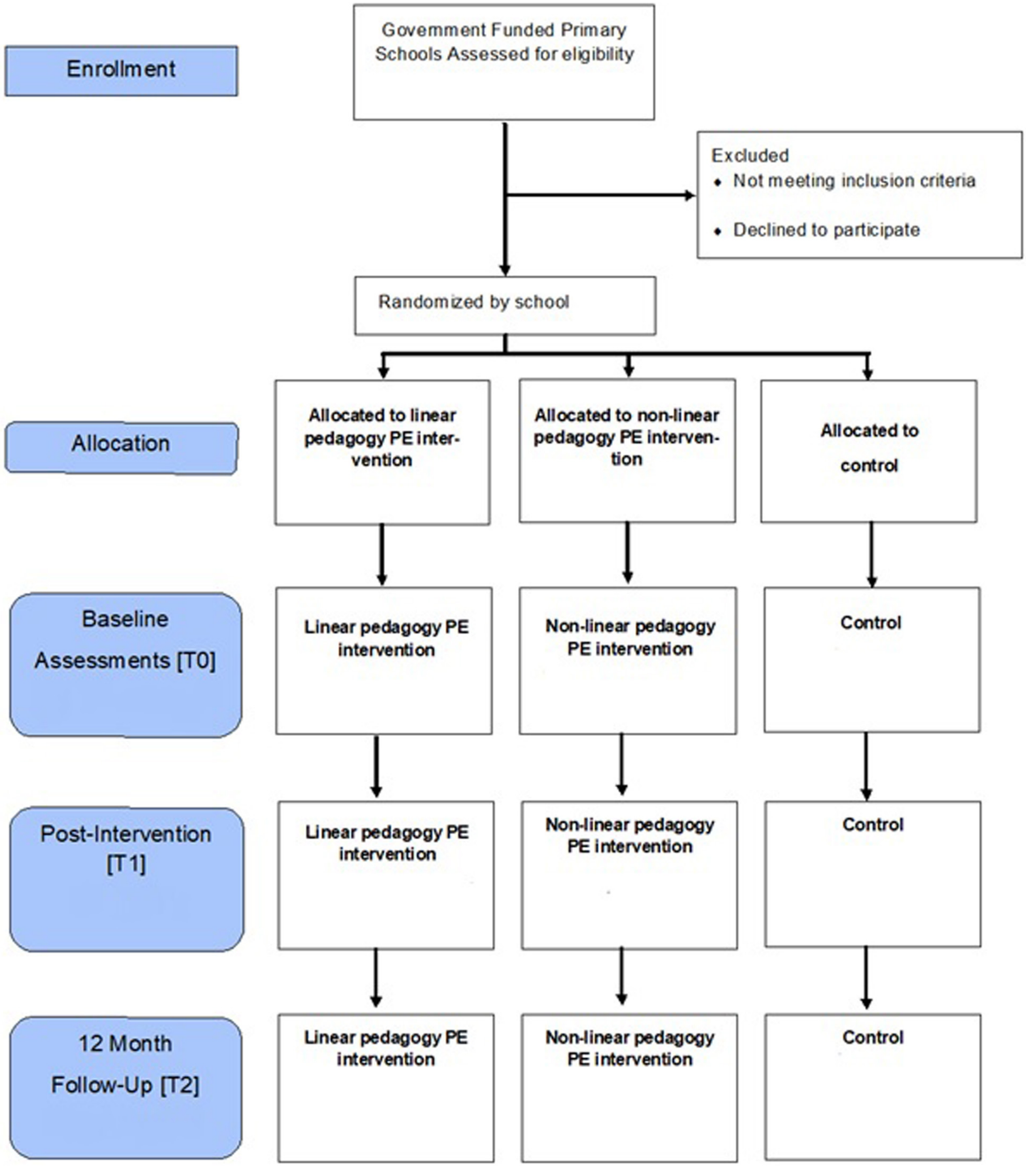

FIGURE 2 | SPIRIT participant timeline.

PE teaching experience in a primary school or sports club setting. Recruited coaches will then be invited to attend a bespoke 5-week training programme. This training aims to develop the coaches' knowledge and skills to deliver either a Linear (operationally through Direct Instruction Model) or Non-linear Pedagogy SAMPLE-PE curriculum.

Prior to the start of the training programme, coaches will be asked to design and deliver a coaching session to year 1 children, which will be video recorded by the research team. The video recordings of the session will subsequently be analyzed by two members of the research team with expertise in both pedagogical approaches. This exercise will enable the research team to determine whether each coach's style of delivery is consistent with direct instruction-based teaching characteristics of Linear Pedagogy or more consistent with inquiry-based and problem-solving teaching characteristics of Non-linear Pedagogy. Coaches will then be allocated to either a Linear or Non-linear 5-week pedagogy training programme based upon their observed teaching style. This programme will comprise 3 h training each week delivered by the research team within a local primary school. Each training session will include a 90-min classroom theory session on either Linear or Non-linear Pedagogy, with pedagogical content knowledge relating to dance, gymnastics and ball sports, and a 90-min practical session of PE delivery to year 1 and 2 primary school children. The practical sessions will consist of a 45-min model lesson delivered in the pedagogical style by a member of the research team who has recognized expertise in PE teaching (Roberts et al., 2019b) followed by the coaches implementing their own lessons in accordance with the respective pedagogy.

All coaches will be provided with a scheme of work, lesson plans and a pedagogical framework for each PE subject (dance, gymnastics, and ball sports), a resource pack covering key elements of their respective pedagogical approach and copies of recorded theory and practical lessons were put online as coaches' resources. A key aspect of the coaches training is the DIFFerentiation framework (see **Table 1**). Coaches will be trained on how they should utilize powerful teaching strategies of demonstration, instruction, and feedback in line with their respective pedagogies (linear or non-linear). This framework was based upon research from either a cognitive approach or ecological approach to motor learning. Coaches will be asked to complete a self-reflection either via diary or audio recording (Gibbs, 1988) each week concerning their implementation of the respective SAMPLE-PE pedagogy principles. This self-reflection will form the basis of discussions in weekly meetings with a member of the research team, alongside any changes necessary to the next week's lesson plans. Coaches will also have the opportunity to access telephone support and a critical friend from the research team throughout the intervention delivery schedule.

Linear Pedagogy

The SAMPLE-PE Linear Pedagogy intervention postulates that movement learning is a process that unfolds in identifiable linear phases (Schmidt, 2019). The Direct Instruction Model pedagogical approach will be used by coaches to create a PE environment where the learner first replicates the coaches' technique, as well as scaffolding activities; starting with low environmental variability, as skill improves the learner will be placed into incrementally more variable and dynamic environments. To support the coaches' learning design and delivery, they were trained to utilize three models: Fitts and Posner's stages of learning (Fitts and Posner, 1973), Gentile's taxonomy (Gentile, 2000) of movement skills, and the challenge point framework (Guadagnoli and Lee, 2004).

Coaches will be trained to identify children in each of Fitts's and Posner's three stages of learning (cognitive, associative or autonomous) and then, prior to the start of the PE lesson, to use this knowledge to modify lesson activities using Gentile's taxonomy. The 16 categories of the taxonomy lead the coach through a logical sequence of potential progressions and force the coach to consider two main perspectives: the environmental context in which the skill takes place and the function that the movement skill must fulfill. Using Gentile's taxonomy, a coach can manipulate the skill to its simplest form, in which the child has a stable base without any object manipulation and in an environment free from distraction. If the coach believes that a child or class of children have higher competence, they can use Gentilie's taxonomy to create a skill context that is far more challenging, i.e., body in motion, manipulation of an object, and environmental factors dictating movement skill responses (Gentile, 2000). To support children's individual needs during the lesson, coaches utilize the challenge point framework (Guadagnoli and Lee, 2004), which indicates that there is an optimal level of challenge for children to maximize learning in a given activity. Each lesson activity represents different challenges for children at different stages of learning a movement skill. The level of difficulty will be dependent upon a number of key variables: the skill level of the performer, the complexity of the activity, and the environment in which the activity is taking place. The more difficult the activity, the greater the learning potential, though this is related to an increase in task difficulty, and as such, the performance of the learner is expected to decrease. Thus, learning is maximized in PE when a child is optimally challenged. This framework supports coaches to critically assess if learning is taking place and consider how they can support a child to maximize learning.

The Linear Pedagogy curriculum was guided by four principles:

(1) There is a correct optimal movement pattern for each foundational movement skill. This is based on the idea that is there is a movement trace that acts as a reference of correctness to guide a child's movement. The coach therefore relies heavily on demonstrations of an optimal movement pattern as this offers a unique opportunity for learners to gather information about appropriate coordination patterns and task requirements which can benefit performance (Sweeting and Rink, 1999; Hayes et al., 2008).
(2) Movement skills are broken down or simplified into key components of a skill for learning, as performing an optimal movement pattern is often beyond the reach of children who are in the early stage of learning a skill.
(3) Movement variability is viewed as noise in the system, which the child has to reduce in their quest toward mastery of a skill. The coach overcomes this by repetitive practice of the skills, which gradually reduces the amount of variability in the system, and the result is an efficient, reliable and accurate movement skill performance.
(4) The focus of attention when performing a movement skill. The majority of research in this area highlights that promotion of an 'external focus' generally results in more effective performance and learning of a movement skill (Wulf, 2013). However, individuals in the cognitive phase of

TABLE 1 | DIFFerentiation framework used to support coaches teaching behaviors in the linear and non-linear pedagogy SAMPLE-PE curriculums.

Linear pedagogy			Non-linear pedagogy		
General assumptions ('DIFFerentitaion')	**Children in the autonomous and associative stage of learning**	**Children in the cognitive stage of learning**	**General assumptions ('DIFFerentitaion')**	**High motor competence children**	**Low motor competence children**
(Fitts and Posner, 1973)			**(Newell, 1986)**		
Demonstration **Isolated demonstrations of a motor skill by an adult or competent child is to be promoted as it offers a unique opportunity for learners to gather information about appropriate coordination patterns which could benefit performance.** (Shea et al., 1999)	Demonstration provided after practice of a task lead to stronger retention of learning than demonstration prior practice (Blandin et al., 1999)	Demonstration of a skill by an individual presenting high proficiency is beneficial for motor learning. (Blandin et al., 1999)	**Demonstration** **Adult demonstration is avoided as NLP encourages more than one optimal way to move in a functional manner.** (Williams and Hodges, 2005; Chow et al., 2016)	No demonstration is given as NLP suggests that it is more or less redundant as they are at the level where further demonstration will no longer provide them with useful information. (Chow et al., 2016)	A few highly competent children to demonstrate the movement in context so that the observing moderate to low competent children can see what they could do within their own movement. (Chow et al., 2016)
Instruction **The use of instruction should have both an internal (skill focus) and external focus of attention is allowed.** (Beilock et al., 2002; Wulf, 2007)	Verbal instructions should focus on movement outcomes rather than on the movements required by the task. (Beilock et al., 2002)	A skill focus instruction is encourage to support early acquisition of the skill as it has been found to be more effective in skill execution. (Beilock et al., 2002)	**Instruction** **The use of instruction is not encouraged if it is needed it should be short and not be prescriptive. Instead coaches were encouraged create games, scenarios and to manipulate task constraints to promote skills being learnt implicitly.**	Use of questioning and external focus as it allows children to problem solve toward a movement solution. (Chow et al., 2016) Coach use STEP framework to manipulate task constraints	If the child has no previous experience of the motor skill, the use of analogies can help as it chunks a large amount of information together that frees up mental capacity providing an external focus of attention. (Chow et al., 2016)
Feedback and Frequency **Feedback is a powerful tool in the coaches toolbox and should be used at the coaches discretion based on their judgment of a child's motor competence. Feedback can either take the shape of knowledge of results or knowledge of performance.** (Sherwood, 1988; Sullivan et al., 2008)	Feedback should be provided only when error are large enough to warrant attention. (Sherwood, 1988)	Providing verbal feedback after each trial or as much as possible during early stages of acquisition is a priority (Sullivan et al., 2008) Practitioner should identify the component of the skills that needs to be learned, determine which is most critical for learning and prioritize feedback about the critical component of the task though this should not happen after every trial. (Weeks and Kordus, 1998)	**Feedback and Frequency** **Feedback should focus on children finding different movement solutions. Feedback is kept to a minimum and only used when children get stuck or to create instability in movement pattern.**	External feedback should only be given if they miss the mark. If they achieve the desired outcome, feedback is not necessary (Hodges and Franks, 2001)	Feedback should never be corrective. The coaches feedback should be minimal and if used should promote an external focus of attention. As with instructions analogies can be useful to support learning. Coaches can also utilize STEP framework to manipulate task constraints (Chow et al., 2016)

movement skill learning have been found to benefit from an internal focus of attention, e.g., a focus on the foot contact if dribbling a football (Beilock et al., 2002). Therefore, the SAMPLE-PE Linear Pedagogy curriculum coaches will be trained to create an internal focus of attention for children identified as in the cognitive phase of skill development (i.e., children with low movement competence), while for children progressing beyond this stage (i.e., children with higher movement competence), coaches focused on an external attention of focus.

The Linear Pedagogy PE curriculum was successfully trialed with year 1 children across three primary schools in summer 2016. A copy of the lesson plan can be found in **Supplementary File 1**.

Non-linear Pedagogy

Ecological dynamics considers individuals (or at a higher level of analysis, a class of children) to be complex and adaptive systems (Davids et al., 2012). If this theoretical premise is accepted there is, from a learning design perspective, considerable uncertainty as to how any particular PE lesson will unfold, and consequently lesson plans should act as a guide, rather than being adhered too strictly at the cost of learning opportunities. Coaches therefore need to adopt a frontloaded approach, whereby they consider in advance how any changes within the PE lesson may alter the learning of each child. While this may seem like an impossible task, there are some consistent variables across schools (e.g., class sizes, lesson duration, national PE curriculum objectives). Moreover, within the classroom there will be common constraints acting upon children such as their age, socio-economic demographic, and the school environment, which either facilitate or hinder motor learning. The research team and coaches will work together to identify common constraints for year 1 children, creating an expected range of variation that the coach could plan for and exploit during their PE lessons, allowing them to design more individualized and meaningful movement experiences for their children. It is important to highlight that this approach recognizes that it is impossible to repeat a movement identically from one attempt to the next (Newell, 1986). Thus, accepting variability in movement is central and the coaches' role is to encourage participants to adapt their movements and continue to improve their technique.

In order to help the coaches deliver the Non-linear Pedagogy curriculum, they will be trained to utilize two models: Newell's (Newell, 1986) model of motor learning, and the Space, Task, Equipment and People (STEP) framework (Youth Sport Trust, 2018). Newell (1986) model of motor learning is based on Ecological Dynamics and will be used to teach coaches that high movement competence is represented by a child's ability to be creative and adaptable whilst succeeding in their performance of movement skills. Coaches will be trained to identify if children's movement behaviors are in the coordination, control or skill stage of learning, and subsequently individualize the PE activity toward a child's particular level of competence by changing one or more task constraints. The STEP framework (Youth Sport Trust, 2018) will support the manipulation of task constraints by increasing or reducing the likelihood of affordances, with the aim of enabling children to effectively solve movement problems.

Alongside these models, the Non-linear Pedagogy curriculum is underpinned by five core pedagogical principles:

(1) A representative learning design. Arguably, a common representative learning design for young children within a PE setting is fun (Headrick et al., 2015; Beni et al., 2017; Foweather and Rudd, 2020). Representative learning design also highlights the importance of skill transfer between multiple settings. For this to occur, it is important that there is a behavioral correspondence between learning and the child's other performance environments, such as the playground, afterschool clubs and sport clubs.
(2) Movement-perception coupling must be maintained when performing skills. This means that skills are practiced in their entirety rather than broken down into component parts or in decontextualized fashion. Movement-perception coupling is seen as a micro (skill level) equivalent of the macro (environment) representative learning design. From a macro perspective, the movement-perception coupling is maintained, for example, within gymnastics lessons by having all equipment present throughout the duration of each lesson, improving their ability to self-regulate their behavior. At the level of the microstructure of practice, the coach does not prescribe the type of movement skill that the child should learn. Instead, the coach promotes creativity and exploration through the use of scenarios and/or mini-games that encourage children to explore and experiment with a broad range of movement skills, meaning movements are learnt in context, and the coach does not isolate skills or develop them by separating into components. Alongside this the coach employs the use of analogies and open-ended questions in the effort to encourage problem solving from the child rather than telling the child exactly what to do.
(3) An external focus of attention is considered necessary to support the acquisition of both creative and functional movement skills. Profeta and Turvey (2018) suggest that if the learner allocates attentional resources to the task and environment rather than to the own movements, movement coordination and control is delegated to the lower levels of the central nervous system where movement is less conscious and learning occurs implicitly. An external focus of attention allows for self-organization of movement patterns to meet the goal of the task, whilst an internal focus of attention promotes a conscious process which is believed to lead to an undesirable breakdown of movements (Wulf, 2007; Chow et al., 2016). To develop functional and adaptive movements, coaches were trained to create mini-games within the lessons, and to utilize and build upon teaching methods such as analogies and questions. These type of activities create an external focus of attention.
(4) The application of constraints – boundaries or features that encourage the development of movement competence. There are three types of constraint: individual, environmental, and task (Pesce et al., 2016b). The

coaches are able to make decisions on what task constraints to manipulate based upon their observations of children's interactions with their environment and using their knowledge of Newell's stages of learning and the STEP framework (Newell, 1986; Youth Sport Trust, 2018). For example, the coach could reduce or increase the playing Space, alter the rules of the Task, use different sized Equipment and/or change the number of People playing the game.

(5) Infusing perturbations within the learning process. This means that if the coach observes a child demonstrating a stable and functional movement skill, the coach will act to destabilize the skill by altering task constraints or changing the task goal. Changing task constraints will result in new affordances. It is important that the coach understands that it is acceptable for different children to display different movement solutions to the same task and that regression in skill is inevitable when altering constraints (such as equipment). As long as the skill is functional and achieves the outcome of the lesson, then it is to be accepted as a pertinent solution.

The Non-linear Pedagogy PE curriculum was successfully trialed with year 1 children across three primary schools in summer 2016. A copy of the lesson plan can be found in **Supplementary File 2**.

Control (n = 6 Schools)

Control schools will be asked to continue with their usual PE curriculum provision, and timetable and deliver 2 × 60 min PE lessons per week for 15 weeks. The control schools follow current national curriculum aims for PE in Key Stage 1 (early primary), which state that: *'Pupils should develop fundamental movement skills, become increasingly competent and confident and access a broad range of opportunities to extend their agility, balance and coordination, individually and with others. They should be able to engage in competitive (both against self and against others) and co-operative physical activities, in a range of increasingly challenging situations'* (Department for Education, 2013). Information pertaining to the PE curriculum being delivered in control schools will be collected as part of a process evaluation (described later in secondary outcomes).

Outcomes

Trained research assistants will undertake 2–3 days of data collection at participating schools across three time-points (see **Figure 1**). Demographic characteristics including child's age, gender, ethnicity, and home postcode (used to classify children into deciles of deprivation level using the English indices of deprivation: Ministry of Housing Communities Local Government, 2018) will be collected at baseline through parent consent forms. A number of primary and secondary outcomes are measured through the study.

Primary Outcome

Movement competence

Movement competence will be assessed through a battery of assessments to examine both technical movement proficiency and movement creativity across different domains (locomotor, object-control, and stability skills). All movement competence assessments will take place during school hours within the school hall or playground and video-recorded for later analysis. Trained research assistants who have established acceptable agreement (80%) in terms of intra-rater and inter-rater reliability with pre-coded videos, will complete analysis of video recordings.

Movement proficiency (technique) will be assessed using the Test of Gross Motor Development-3 (TGMD-3; Maeng et al., 2016) and the Test of Stability Skills (Rudd et al., 2015). Specifically, six locomotor (run, gallop, hop, skip, horizontal jump, slide) and seven object-control (two-hand strike, one-hand strike, one-hand dribble, two-hand catch, kick, overhand throw, underhand throw) skills will be assessed using the TGMD-3 (∼30 min to complete). Proficiency at stability skills will be assessed using the three tasks (log roll, rock, back support) from within the Test of Stability Skills (∼15 min to complete). The psychometric quality of these assessments has been well-established (Rudd et al., 2015; Maeng et al., 2016). Participants will receive a verbal explanation and single demonstration from the assessor and are then given one practice attempt before undertaking two trials of each skill.

Movement creativity will be assessed using the Divergent Movement Ability Assessment (Cleland, 1990), which requires children to complete three stations, a stability skill station, a locomotor skill station and object control skill station (∼15 min to complete). In the stability station, children are asked to make as many shapes on or around the bench as they can. In the locomotor station, children are challenged to find as many different ways to move around the obstacle course as possible. Finally, in the object-control skill station, children will be asked to play with a large ball in a designated area, showing all the different skills and ways that they can play with the ball. For every station, children will complete two 90 s trials, during which, every 30 s the child will get a predefined prompt from the research assistant to support and encourage the child.

Secondary Outcomes

Physical activity

Participants will be asked to wear a monitor (accelerometer; ActiGraph GT9X, ActiGraph, Pensacola, FL, United States) on their non-dominant wrist continuously for 7 days to measure physical activity at each time point. Participants will be asked to wear their monitors at all times, and to remove them only for water-based activities. Accelerometers will be initialised at a sampling frequency of 30 Hz. During the monitoring period, children's parents are asked to keep a diary in order to record any times when the monitor is taken off, any activities completed whilst the monitor is removed (e.g., swimming, bathing), and the time the monitor is put back on. A member of the research team will return to the school at the end of the 7-day period to collect the monitors and diaries. Accelerometry data will be used to examine within school, leisure (after-school and weekend), and habitual (total) physical activity levels. Children will be included in the analyses if they have worn the monitor for at least 10 h per day over 3 days, including one weekend day. Time spent in sedentary, light, moderate and vigorous activity will be determined using age- and- population-specific raw acceleration cut-points for the wrist-worn ActiGraph, developed through an ongoing research study (Crotti et al., 2020).

Perceived competence

Perceived physical competence (higher order construct) will be assessed using the corresponding subscale within The Pictorial Scale of Perceived Competence and Social Acceptance for Young Children (Harter and Pike, 1984). The Physical Competence subscale includes items 3, 7, 11, 15, 19, and 23 from the overall Pictorial Scale, and takes approximately 3 min to complete. Each item is scored on a four-point scale, where 4 represents the highest degree of perceived competence. The subscale score is computed by adding values of child responses and ranges from 6 to 24.

Perceived Skill Competence (lower order construct) will be assessed by the Pictorial Scale of Perceived Movement Skill Competence for Young Children 3rd Edition (Harter, 1978; Barnett et al., 2015). The Scale consists of 13 items with two subscales of six and seven items for "Locomotor Skill Perceived Competence" and "Object-Control Skill Perceived Competence," respectively. Each item is scored on a four-point scale, where 4 represents the highest degree of perceived competence. Subscale scores are computed by adding values of child responses and range from 6 to 24 for locomotor and 7 to 28 for object control (higher values indicate higher perceived competence). All 13 items are summed to generate the Perceived Movement Skill Competence scale score, which ranges from 13 to 52 (higher values indicate higher perceived competence). The Pictorial Scale of Perceived Movement Skill Competence for Young Children is a valid and reliable instrument to assess perceived movement competence in young children (Barnett et al., 2015), taking around 5–7 min to complete.

Motivation and psychological needs satisfaction

Self-determined motivation and psychological needs satisfaction are difficult to assess in young children as traditional self-report measures are not appropriate (Sebire et al., 2013). Therefore, following Noonan et al. (2016) and Parker et al. (2018), we have developed a child friendly and age-appropriate Physical Education Motivation Assessment Tool (MAT-PE) to assess self-determined motivation for PE (Fitton-Davies et al., Unpublished). All children in each year 1 class will be asked to draw a picture of "what they like about PE" on one side of a piece of A4 paper and conversely "what they don't like about PE" on the other. Due to the time necessary to administer and analyze MAT-PE, a random sub-sample of participants ($\sim n = 5$ per class) will be selected to participate in 1:1 activities with a researcher. This random sample will be selected from a pool of research children, whom the class teacher will have identified as wishing to talk to researchers, and with a sufficient level of English verbal skills to be able to have a conversation with an adult. The 1:1 activities will take place in a quiet open space outside of the classroom (e.g., school library) where the researcher can be overlooked but not overheard and the conversation between the child and researcher will be recorded using a Dictaphone. The 1:1 activities will commence with an icebreaker activity to relax and build rapport between the researcher and child (a PE themed pair-matching card game). The researcher will then ask the child to describe their drawing(s) and ask questions in order to ascertain information about the picture stimulated from its content. This will be followed by a series of activities including the use of resource cards to explore needs satisfaction during PE lessons in relation to (i) relatedness, (ii) competence, and (iii) autonomy (Ryan and Deci, 2000). The final activity will involve each child being presented with a picture that represents each level of regulation along the self-determined motivation continuum that is coupled with a stem (e.g., '*I do PE because it is fun*'). Each stem will be read aloud to the child and clarification given if needed. The child will then be asked to pick their favorite reasons for taking part in PE, which they are subsequently asked to rank (first being most important to them, last being least important). Each 1:1 session will last around 15–20 min. Audio recordings will be transcribed and content analysis will be conducted through the use of a codebook so as to determine changes in basic psychological need satisfaction and self-determined motivation. Thematic analysis will also be conducted so as to capture information from the children around their PE experiences which may have been impacted by the intervention.

Executive functions

Under the guidance of a trained member of the research team (1:1), in a quiet space outside the classroom (e.g., the library), individual children will be asked to work through three age-appropriate activities from the National Institute for Health (NIH) Toolbox (Gershon et al., 2010) to assess the three core executive functions. The NIH Toolbox is a comprehensive set of neuro-behavioral measurements that quickly assess cognitive, emotional, sensory, and motor functions from the convenience of an iPad. Each child will complete three cognitive activities lasting 15 min in total: inhibitory control is assessed through The Flanker Test (3 min), cognitive flexibility through the dimension card sort (4 min), and working memory via a list sorting task (7 min). The NIH toolbox has well-established validity and reliability for use with children aged 3–15 years (Weintraub et al., 2013).

Self-regulation

Children's self-regulation will be assessed using the Strength and Difficulties Questionnaire (SDQ; Goodman, 1997; Stone et al., 2010), which will be completed by class teachers for each participating child at each time point. The SDQ is a brief behavioral screening questionnaire consisting of 25 items within five subscales (emotional, conduct, hyperactivity, peer and prosocial), and has demonstrated good reliability and validity across several studies (Essau et al., 2012). There are five items on each subscale with each item scored 0, 1, or 2. Scores therefore range from 0 to 10 for each subscale, with 10 indicating higher levels of difficulties (emotional, conduct, hyperactivity, peer subscales) or strengths (prosocial subscale) and 0 indicating lower levels. A total difficulties score is also generated by summing scores from all the scales except the prosocial scale, with scores ranging from 0 (low) to 50 (high).

Each child's self-regulation will also be assessed by researchers using the RCS (Lakes, 2012, 2013). The RCS is an observer-rated measure of children's responses to challenges in an obstacle course. The course is designed to vary demand and challenge and takes 10–15 min to complete in a school hall/outside school playground. The trained observer rates children on 16 items comprising bipolar adjectives (e.g., Vulnerable—Invincible), which are rated on seven-point scales (scored 1–7). Negatively worded items are reversed prior to aggregation, so that possible scores on all items ranged from 1 to 7, with higher scores indicating greater self-regulation. Items are summed to assess self-regulation within three subscales: "Cognitive" (six items, scoring range from 6 to 42), "Affective" (seven items, scoring range from 7 to 49) and "Physical/Motor" (three items, scoring range from 3 to 21).

Anthropometrics

Children's height, sitting height, waist and body mass will be measured with an accuracy of 0.1 cm and 0.1 kg, respectively (Lohman et al., 1988). Height and sitting height will be assessed with a portable stadiometer (Leicester Height Measure, SECA, Birmingham, United Kingdom) and body mass will be assessed using digital scales (Tanita WB100-MA, Tanita Europe, Netherlands). Waist circumference will be measured around the navel region. Measurements will be taken without shoes and whilst wearing light clothing, taking approximately 5 min. Height and weight values will be used to examine weight status through the International Obesity Task Forces age and sex adjusted body mass index (BMI) growth-reference to enable international comparisons (Cole et al., 2000).

Process Evaluation

Informed by the RE-AIM framework and previous literature (Glasgow et al., 1999; Linnan et al., 2002) as well as by the UK Medical Research Council guidance for process evaluation that advocates exploring context, implementation, impact and outcomes (Moore et al., 2015) a pragmatic process evaluation design will examine intervention *context*, *reach*, *dose*, *fidelity*, *acceptability implementation*, *impact*, *acceptability,* and *sustainability*.

Reach will be assessed using school administrative data on child demographics and school registers. Teachers (control schools) and SAMPLE-PE coaches (intervention schools) will be asked to log the number of PE lessons implemented at each school, and the duration of each PE lesson in minutes to determine. Direct observations of PE lessons by researchers and coaches' logs will be used to examine *dose delivered*, *fidelity* and participant responsiveness (*dose received*). Specifically, in each intervention and a subsample of control schools, three lessons from each class (one in every 5-week phase of delivery) for a total of approximately 50 lessons will be audio- and video- recorded, using a wireless microphone and video camera (situated to capture the whole class and deliverer).

Video footage will subsequently be analyzed by trained researchers to assess whether the intervention was delivered as intended (*fidelity*) using developed observation checklists for Non-linear and Linear pedagogies, respectively. Intervention fidelity will be confirmed if (i) the Non-linear pedagogy intervention schools' PE lessons show greater implementation of Non-linear pedagogical principles than Linear and control schools PE lessons, and (ii) the reverse is true for Linear pedagogy intervention schools' PE lessons. Video recordings of PE lessons will also be retrospectively coded using established observation checklists to examine SAMPLE-PE coach (intervention schools) and teacher (control schools) behaviors in relation to promoting children's moderate-to-vigorous physical activity (SOFIT+; Weaver et al., 2016; Fairclough et al., 2018) and supporting or thwarting children's psychological needs for relatedness, competence, and autonomy (Smith et al., 2015). Researchers will also record the number of children participating in lessons, and the number of staff present and collect data on the themes and types of activities undertaken within the control group's PE lessons.

Participant responsiveness. refers to how responsive participants are to an intervention (Durlak and Dupre, 2008). For the purposes of this process evaluation, we will examine participant responsiveness in terms of children's self-determined motivation, psychological needs satisfaction and physical activity levels within the observed PE lessons (15 lessons at each three time points). Psychological need satisfaction and enjoyment of the PE lesson from a child perspective will be assessed at the end of each observed PE lesson. Physical activity will be assessed during each observed lesson. In terms of self-determined motivation, immediately following the lesson, all research children (those within both experimental arms and three control schools) will complete brief measures of relatedness, autonomy and competence need satisfaction on a 1:1 basis with trained researchers. For relatedness, we will look to explore the quantity of social interactions. In line with Sebanc (2003) children will be asked by a member of the research team to identify which children within their class they worked with during that lesson from a school class photo list. For competence, children will be asked *how good were you at things during that PE lesson?* This will be measured on a 1–5 star rating scale: 1 being not very good and 5 being very good. For autonomy, children will be asked *did you get to do any choosing during that PE lesson?* The answer format is on a two-layer response where they first choose either 'yes' or 'no.' Depending on their initial response, they will be asked if this is 'sometimes yes' or always yes,' or 'sometimes no,' or 'always no.' For enjoyment, as children leave the PE lesson, they will be asked to tap on 1 of 3 posters situated on a wall by the exit door displaying an emoji face depicted either as boring, ok or fun. Children's actions will be video recorded by a research assistant. To assess participant responsiveness in terms of physical activity levels, a sub-sample of children (50% of the research participants in each class) will be randomly-selected to wear an Actigraph GT9X+ accelerometer (Actigraph, Pensacola, FL, United States) on their non-dominant wrist within each PE lesson observation. The time that the teacher commences and ends the lesson will be recorded by a research assistant, and used to calculate the proportion of time children spent in moderate-to-vigorous physical activity.

A qualitative methodology, will be utilized to explore the experiences and perceptions of key stakeholders within intervention schools with regards to *context*, *fidelity*, *implementation*, *impact*, and *acceptability*, and *sustainability*. Utilizing the interpretivist paradigm, it is recognized that human action and interaction such as PE lessons, is experienced subjectively evaluated through individual meaning making (McKenzie et al., 1997). Thus, the effectiveness of an intervention, such as SAMPLE-PE, is inherently linked to the experiences and perceptions of key stakeholders such as teachers. Collecting and analyzing these perceptions, through interpretivist qualitative methods is, therefore, an essential part of a process evaluation (Cheng and Metcalfe, 2018). To that end, qualitative methods are an appropriate methodology to gather data (Smith and McGannon, 2018).

Through interviews, researchers will explore: (1) the *fidelity* of the intervention; (2) *implementation* and *impact*; and (3) *acceptability* and *sustainability* of *Linear* and Non-linear pedagogy intervention curriculums. The sample is purposive in that individuals with the experience of intervention will be recruited. It is also iterative, because as the intervention proceeds, the sample size may increase to include other stakeholders, e.g., teaching assistants. Importantly, the process evaluation not only gathers the experiences and perceptions of stakeholders such as teachers, but a process evaluation can also describe the context in which interventions were experienced. This will be captured through structured interviews with head teachers of intervention schools who are well-placed to describe the school as a whole. These interviews will explore school policy, funding, support, equipment, time allocation for PE, and potential for scale-up of the interventions, as well as any other aspects of the complex school environment that may have influenced the intervention and outcomes.

To collect interview data, a combination of skype, face-to-face and email interviews will be utilized. More specifically, participants will be offered the opportunity to share their experiences and perceptions in the format that best enables them to do so. This choice enables participants to exercise their autonomy (Orb et al., 2001). Structured interview schedules have been developed (**Supplementary File 3**) in order to focus attention on the context, fidelity, implementation, impact, acceptability and sustainability of the intervention across both *Linear* and Non-linear Pedagogy schools. The use of a structured interview schedule will ensure that interviews will be conducted in a consistent manner regardless of medium, e.g., face-to-face or email. The structured format of the interview schedule will also ensure that any researcher bias is 'managed' in order to maintain equipoise as far as possible (Eborall et al., 2014). Interviews will be transcribed and analyzed using thematic analysis (Clarke and Braun, 2013). To ensure rigor during the data collection and analysis processes, co-researchers will act as critical friends (Smith and McGannon, 2018). This will involve reviewing the structured interview schedule to identify leading questions, and reviewing coding and themes to ensure verisimilitude with the data.

Data Analysis

Linear-mixed models will be conducted to examine the effects of the SAMPLE-PE intervention on the main outcomes of the study (i.e., movement competence development) in the short-term (post-intervention) and medium-term (at follow-up). Separate analyses will be conducted for each outcome measure. Mixed models are used to account for the nested structure of the data. The significance level will be set $p < 0.05$ for all statistical analyses. Regression coefficients for the group variables (with a "0" and "1" dummy coding) will reflect average differences in the outcome variables over time. Potential effects of confounding factors such as sex, age, ethnicity, and deprivation will be examined in the hierarchical linear regression analyses. Mediation analyses will be conducted to examine hypothesized mediating pathways that might explain the expected intervention effects in non-motor (cognitive and affective) domains through gains in actual (Pesce et al., 2016a; Sánchez-López et al., 2019) and perceived movement competence. Attrition analyses comparing children who completed the study and those who dropped out will also be performed. Analyses will be conducted using R and follow an intention-to-treat approach.

DISCUSSION

The SAMPLE-PE study aims to examine the efficacy of two different pedagogical approaches to PE (Linear or Non-linear) upon children living in deprived areas. Each approach is informed by movement learning theories used to support the design of learning experiences which, beyond mere movement learning outcomes, are also tailored to support the development of non-motor (cognitive affective) aspects of children's physical literacy journey. In this frame of expected outcomes in physical and wider domains, the study also aims at providing important insights into the inter-connected nature of physical, affective and cognitive developments that can be elicited by SAMPLE-PE. To deliver these pedagogical models effectively, the coaches will need to possess an in-depth knowledge of the respective pedagogy and learning design principles to improve movement competence. Coaches will receive a comprehensive and extensive training programme from the research team to enable them to deliver the SAMPLE-PE intervention curriculums. A potential limitation to the evaluation is that we do not have the capacity to examine the fidelity of the training, though we will measure the coaches' ability to deliver the interventions in accordance with the corresponding pedagogy via direct observation of a sub-sample of PE lessons.

The findings of this study should further develop pedagogical practice, inform learning design within PE, shed new light on how to enhance children's development of movement competence and, more broadly, lead to a better understanding of how to foster physical literacy in the children who need it most. As such, the study could have significant implications for the primary school PE curriculum and for career professional development and training offered to sports coaches and specialist/generalist primary school teachers. Furthermore, the comprehensive mixed methods process evaluation and use of robust outcome measures should provide novel, inter-disciplinary insight into movement competence as a driver of perceived competence, motivation, cognition and physical activity, and extend current knowledge about the effectiveness of PE interventions. The study has therefore the potential to raise standards and the value of PE, and progress to a scaled-up, effectiveness trial involving classroom teachers in the future.

AUTHOR CONTRIBUTIONS

JR and LF conceived the study. All authors were involved in the design of the study protocol and assisted with the drafting and revising of the manuscript, read and approved the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2020.01228/full#supplementary-material

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Motor-Enriched Encoding Can Improve Children's Early Letter Recognition

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It is not known how effective specific types of motor-enriched activities are at improving academic learning and early reading skills in children. The aim of this study was to investigate whether fine or gross motor enrichment during a single session of recognizing letters "b"/"d" can improve within-session performance or delayed retention the following day in comparison to letter recognition practice without movement. Furthermore, the aim was to investigate children's motivation to perform the specific tasks. We used a randomized controlled intervention study-design to investigate the effect of 10-min motor-enriched "b"/"d" letter training on children's ability to recognize the letters "b" and "d" (n = 127, mean age = 7.61 ± SD = 0.44 years) acutely, and in a delayed retention test. Three groups were included: a fine motor-enriched group (FME), a gross motor-enriched group (GME), that received 10 min of "b" and "d" training with enriched gestures (fine or gross motor movements, respectively), and a control group (CON), which received non motor-enriched "b"/"d" training. The children's ability to recognize "b" and "d" were tested before (T0), immediately after (T1), and one day after the intervention (T2) using a "b"/"d" Recognition Test. Based on a generalized linear mixed model a significant group-time interaction was found for accuracy in the "b"/"d" Recognition Test. Specifically, FME improved their ability to recognize "b"/"d" at post intervention (T0→T1, $p = 0.008$) and one-day retention test (T0→T2, $p < 0.001$) more than CON. There was no significant difference in change between GME and CON. For reaction time there were no significant global interaction effects observed. However, planned post hoc comparisons revealed a significant difference between GME and CON immediately after the intervention (T0→T1, $p = 0.03$). The children's motivation-score was higher for FME and GME compared to CON (FME-CON: $p = 0.01$; GME-CON: $p = 0.01$). The study demonstrated that fine motor-enriched training improved children's letter recognition more than non motor activities. Both types of motor training were accompanied by higher intrinsic motivation for the children compared to the non motor training group. The study suggests a new method for motor-enriched letter learning and future research should investigate the underlying mechanisms.

Keywords: motor-enriched, academic learning, children, cognition, letter recognition

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INTRODUCTION

The acquisition and development of reading skills is a central cognitive attribute to society. How much a student reads is a unique and powerful contributor to a variety of academic skills, including oral language, basic reading skills, spelling, content/declarative knowledge, and vocabulary skills (Sparks et al., 2014). Children who learn to recognize and name the letters early demonstrate stronger decoding skills and reading comprehension in later grades (Hammill, 2004; Schatschneider et al., 2004; Piasta et al., 2012). Thus, it is important to identify strategies for improving early reading skills in children.

Development of single word reading can be described as moving through a series of overlapping phases. Here, children successively learn more advanced means for recognizing and learning orthographic words (Ehri, 2008). In the pre-alphabetic phase, children recognize words by their general shape and contextual cues. This strategy has the important limitation that it does not allow the child to read unknown words. In the partial alphabetic phase, word recognition is supported by knowledge of some letters and some letter sounds. In the full alphabetic phase, the child knows all the letters and their sounds and how to blend the sounds into full word pronunciations. This allows them to read unfamiliar words. In the consolidation phase, this process is extended to chunks of letters, for example, representing specific syllables and morphemes. Thus, in all phases past the pre-alphabetic phase, recognition and differentiation of individual letters plays an important role in recognizing whole words (Ehri, 2008).

The ability to recognize letters is therefore important to early literacy development (Hiebert et al., 1984). Especially children's ability to recognize letter names helps them to learn sounds, which requires letter knowledge (Hammill, 2004; Foulin, 2005; Bara and Bonneton-Botté, 2018). Letter naming knowledge is a predictor of learning how to read based upon longitudinal correlations between letter naming and reading achievement in children (Kirby et al., 2008). Weak letter sound knowledge is known to cause difficulties in translations from reading to speaking, and is an important component to pay attention to in order to help children learn to read (Hulme et al., 2012). A study by Badian (2005) concluded that children (8–10 years) with a deficit in recognizing errors in letter orientation were poorer readers than children without this deficit (Badian, 2005). It has been shown that children often struggle especially with learning the letters "b" and "d" and often make a lot of orientation errors with these two letters (Tortorelli et al., 2017). Thus, it is relevant to design a short-term intervention focusing on improving children's ability to recognize and discriminate "b" and "d" (Badian, 2005).

Research shows that motivation plays a central role in literacy development. Motivation can be facilitated by positive learning environments and positive reading experiences (Gambrell, 1996; Chapman and Tunmer, 1997; Guthrie et al., 1999; Marinak et al., 2015). There are different types of motivation with different levels of autonomy and different effects on academic achievement and development (Gottfried, 1985; Ryan and Deci, 2000). Intrinsic motivation implies doing something because it is enjoyable and interesting, more than doing something based upon pressure. Feelings of competence, autonomy, and relatedness are basic psychological needs, which must be fulfilled for sustaining the intrinsic motivation (Deci et al., 1999). It is known that especially intrinsic motivation is associated with higher reading achievements, higher conceptual understanding, and that this type of motivation generates higher ability to persevere when reading tasks become challenging (Gottfried, 1985; Marinak et al., 2015). Classroom based physical activities have shown to be a strategy to increase intrinsic motivation, moreover, fostering executive functions (Vazou and Smiley-Oyen, 2014), especially when the activities are built upon deliberate play (Pesce et al., 2016). Accordingly, several interventions have focused on the potential positive impact of physical activity breaks in addition to cardiovascular exercise to facilitate cognitive performance (for reviews, see Hillman et al., 2008; Pesce and Ben-Soussan, 2015; Pesce et al., 2016), and behavioral effects (Voelcker-Rehage and Niemann, 2013).

Intervention studies with focus on quantitative characteristics of physical activity with the purpose of improving cognitive performance and academic achievement have received a lot of attention (Best, 2010; Donnelly et al., 2016). Less focus has been on more qualitative characteristics of physical activity, where coordinative activities are used within learning sessions (Diamond, 2015). Motor-enriched encoding is one type of learning-model, which could be used.

Motor-enriched encoding, where learning of a subject is combined with meaningful motor activities, has previously shown positive effects in a wide range of different learning paradigms (Beck et al., 2016), for example, conceptual and associative learning, action-sentence learning, and also more academically related vocabulary and foreign language learning (Macedonia and Klimesch, 2014; Mavilidi et al., 2015; Mayer et al., 2015). In both children and adults motor-enriched foreign word learning is facilitated when congruent gestures are used (Macedonia et al., 2011; Mavilidi et al., 2015; Toumpaniari et al., 2015). Mavilidi et al. (2015) demonstrated that pre-school children (age of 5 years old), before the full alphabetic phase, also benefitted from motor-enriched foreign word learning, however, whether letter learning is also positively influenced by pairing encoding with congruent gestures before the full alphabetic phase is not known. Potential positive learning effects of motor-enriched encoding might have several explanations also involving working memory and retrieval processes. One theory is that motor-enriched activities activate not only cortical areas of cognitive control but also a wide range of cortical motor and sensory areas (Engelkamp and Zimmer, 1989; Barsalou, 2008; Macedonia, 2019). These cortical areas are responsible for generation of actions and processing the sensory consequences of the actions this may help encoding by (a) efficient activation of both the visual and phonological subsystems supporting working memory and (b) increased activation of sensorimotor brain areas both during encoding and retrieval (Macedonia et al., 2011; Mayer et al., 2015; Macedonia, 2019). The latter has been shown by Mayer et al. (2015) using functional magnetic resonance imaging (fMRI), reporting that a word recall task at 2-months post-acquisition correlates with increased activation of the left-brain motor cortex and the temporal brain sulcus in adults. The findings by Mayer et al. (2015) supported the multisensory learning theory proposed by Shams and Seitz (2008) that words encoded audio-visually improve performance compared to words encoded audibly (Shams and Seitz, 2008; Mayer et al., 2015). It is assumed that dividing the cognitive load imposed by a learning task across different working memory subsystems (visual and auditory) can prevent negative effects of too high load on one specific subsystem (Baddeley, 2010).

A study within mathematics has shown that hand gesturing during problem solving can prevent too high load on one specific subsystem (Goldin-Meadow et al., 2001). Goldin-Meadow et al. (2001) investigated how gesturing during one task (children had to explain solution to a math problem) impacted performance on another task (remembering words), and showed that children (mean age = 9.91 years) remembered more items when gesturing compared to non-gesturing (Goldin-Meadow et al., 2001).

Interestingly, Mavilidi et al. (2015) found that the effect is dependent on the motor modality used. The study compared whole body motor activity and part body activity (arms and hands) integrated into the academic content. The whole-body activities resulted in the highest scores in a free-recall and cued-recall vocabulary task in preschool children. These findings indicate that there may be a difference in efficacy between the use of fine motor movements and gross motor movements during learning. A recent review identifies a knowledge gap in terms of when and how to incorporate gross motor movement in academic lessons (Mavilidi et al., 2018). The authors state that when movements are not meaningfully or congruently incorporated in the academic lesson, children have more difficulty performing a word recall task (Mavilidi et al., 2015; Toumpaniari et al., 2015). Research on motor-enriched encoding has predominantly focused on word learning and solving math problems while few studies have focused on letter recognition and if so they predominantly focus on writing and tracing letters (Hulme et al., 1987; Bara and Bonneton-Botté, 2018) or have mixed encoding strategies (Kirk and Kirk, 2016). It is, however, not known if motor-enriched encoding can improve reading abilities or letter recognition. The present study will further elucidate this topic of meaningfully integrating fine and gross motor movements into the learning activities focusing on the distinction between "b" and "d."

Based upon current knowledge regarding the benefit of motor-enriched encoding, we hypothesize that 10 min of fine or gross motor-enriched activities can improve recognition of "b" and "d" and distinction between these letters and furthermore higher intrinsic learning motivation for the learning activity more than non motor control activities.

MATERIALS AND METHODS

Participants

The study was conducted with first grade children recruited from eight different classes from three elementary schools in the Copenhagen area. In total 127 children (71 girls and 56 boys, mean age ± SD = 7.61 ± 0.44 years) were included in the study after obtaining written consent from parents, corresponding to 73% of the invited children (see **Table 1** for demographic characteristics within each group). Retention test (T2) at one of the schools was not performed due to practical issues which means that 40 children were excluded from the "b"/"d" Recognition Test at T2. In addition, two children were absent at the day of T2 (**Figure 1**). The study was approved by the local Ethical Committee at University of Copenhagen, Denmark (protocol: 504-0032/18-5000), and was carried out in accordance with the Helsinki Declaration II.

Intervention

All participating children were randomized individually before baseline assessment to receive one of three "b"/"d" training sessions: a fine motor-enriched (FME), a gross motor-enriched (GME) or non motor (CON) condition. All three groups received one-to-one teaching focusing on "b"/"d" for 10 min with one investigator. Budde et al. (2008) demonstrated that 10 min coordinative exercise resulted in a higher attention score than normal sport activities. Based on Budde and colleagues' results the intervention duration of 10 min was chosen for this present study.

The training was not blinded to neither participants nor the investigators. The groups differed in the teaching approach. Children in the FME group were sitting at a table with their elbows resting at the table while trying to find the letters "b" and "d" randomly distributed on a computer screen, while simultaneously pronouncing the name of the letter they touched with their fingers. Using their fingers, the children shaped the letters "b" with left hand fingers and "d" with right hand fingers before touching the screen (**Figure 2**). The GME group was standing at a smartboard and created "b" with their left arm stretched out in the front of the body and their right hand placed at the left elbow. They created "d" by stretching out their right arm in front of the body and placing their left hand at the right elbow (**Figure 2**). Further, they were asked to touch the "b" or "d" on the smartboard, while saying the name of the letter they touched. The CON group searched for the letter's "b" and "d" on a white A4 paper while remaining silent. They were instructed to sit with their arms resting on the table through the 10-min session and were restricted only to use their eyes during the intervention. The investigator carefully observed the children's tracking of "b"/"d"s and helped

TABLE 1 | Demographics for the three intervention groups (CON, FME, GME).

	CON	FME	GME
Participants (*n*)	43	40	44
Age (Years)	7.61 ± 0.44	7.61 ± 0.44	7.62 ± 0.44
Sex (% Boys)	46.51	40.00	45.45
Bilingualism (% Bilingual)	25.58	27.50	27.27
Dominant hand (R, %)	90.70	92.68	88.64

Data reported as mean ± SD. No significant between-group differences were observed for any of the measures. CON, control group; FME, fine motor-enriched group; GME, gross motor-enriched group.

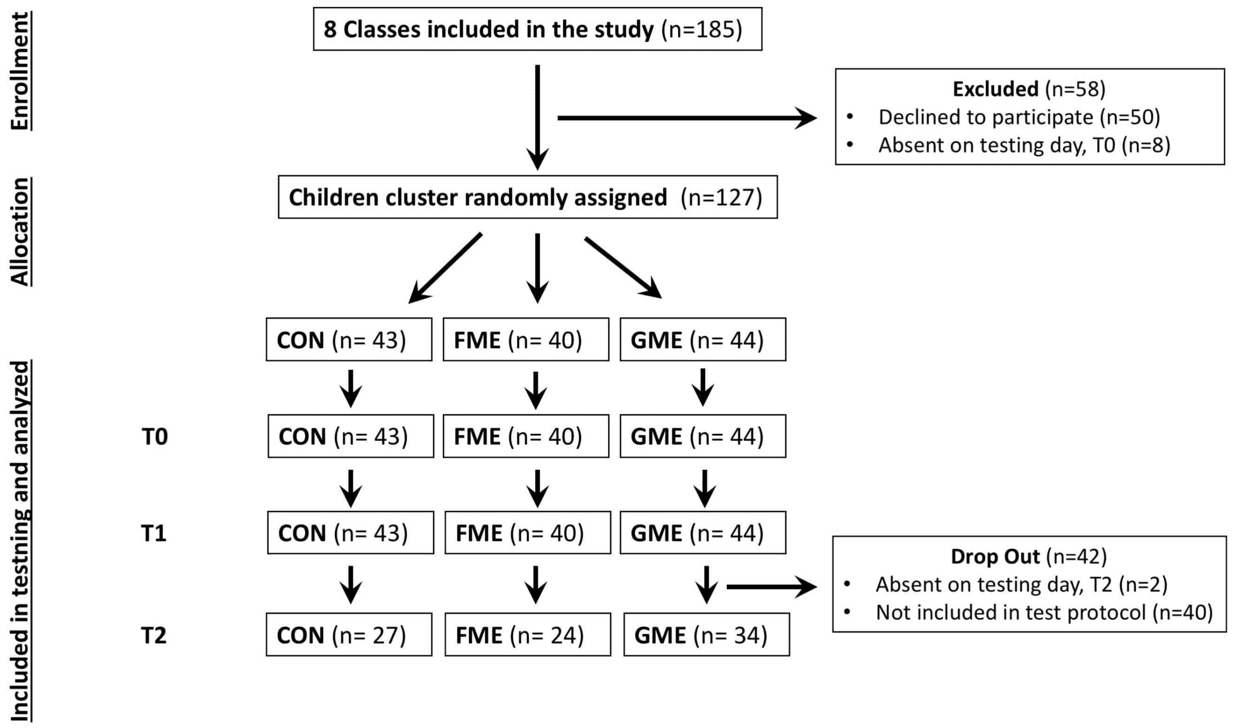

FIGURE 1 | Flow diagram of the study. Retention test (T2) was not performed due to practical issues at one school, which means that 40 children were not performing T2 "b"/"d" Recognition Test.

change the paper, so the children did not have to move (**Figure 2**). All children thoroughly performed the task and no oral feedback was given to any of the three groups. The exact duration and the number of trials completed during intervention were registered.

Test Procedures

Age, sex, handedness, and bilingualism of the children are known to influence reading abilities (Lundberg et al., 2012) and were collected prior to baseline measures. For all three groups (CON, FME, and GME), baseline measures (T0) consisted of a letter fluency test and "b"/"d" Recognition Test. The children then completed one of the three interventions (CON, FME, and GME) and were post-evaluated in "b"/"d" Recognition Test and motivation (T1). The next day (after 20–24 h) another "b"/"d" Recognition Test was completed (T2). The intervention was conducted by six trained investigators. Each investigator performed "b"/"d" training for participants in all three groups (CON, FME, and GME) and performed all the measurements and intervention with the same child.

MEASURES

Letter Fluency

To estimate the children's letter recognition at T0 a Danish version of letter fluency test was used (Good and Kaminski, 2002; Poulsen and Jensen, 2015). The test consisted of 116 uppercase and lowercase letters placed in rows of 10 letters on white A4 paper. The children were told to name as many letters as possible in 1 min. The test was conducted individually under supervision from the investigator. To get familiar with the test, a pre-test consisting of 10 letters were administered to the child before the actual test. The total number of all correctly named letters from the main test were used as an outcome measure.

"b"/"d" Recognition Test

A simple "b"/"d" Recognition Test was developed for the present study by the research group. The "b"/"d" Recognition Test was applied to evaluate the children's ability to recognize the letters "b" and "d." A Cronbach's Alpha coefficient was used to test the reliability of the "b"/"d" Recognition Test from T0, T1 and T2 ($\alpha = 0.7$).

The test was completed on a computer in a one-to-one session between the child and an investigator. The children were comfortably placed in front of a 13.3-inch laptop at a distance that allowed them to press the response buttons on the keyboard with their index fingers, with their elbows resting on the edge of the table.

The laptop presented the stimuli using E-prime (Psychology Software Tools, Pittsburgh, PA, United States). Stimuli "b"/"d" letters were black 90 mm $\times$ 10 mm letters. The stimuli letters were d, b, p, q, m, and n, and presented in the center of the screen on a white background. The children completed a single block of 32 letters at T0/T1 (10 b, 10 d, and 12 p/q/m/n) and 60 letters for timepoint T2 (20 b, 20 d, and

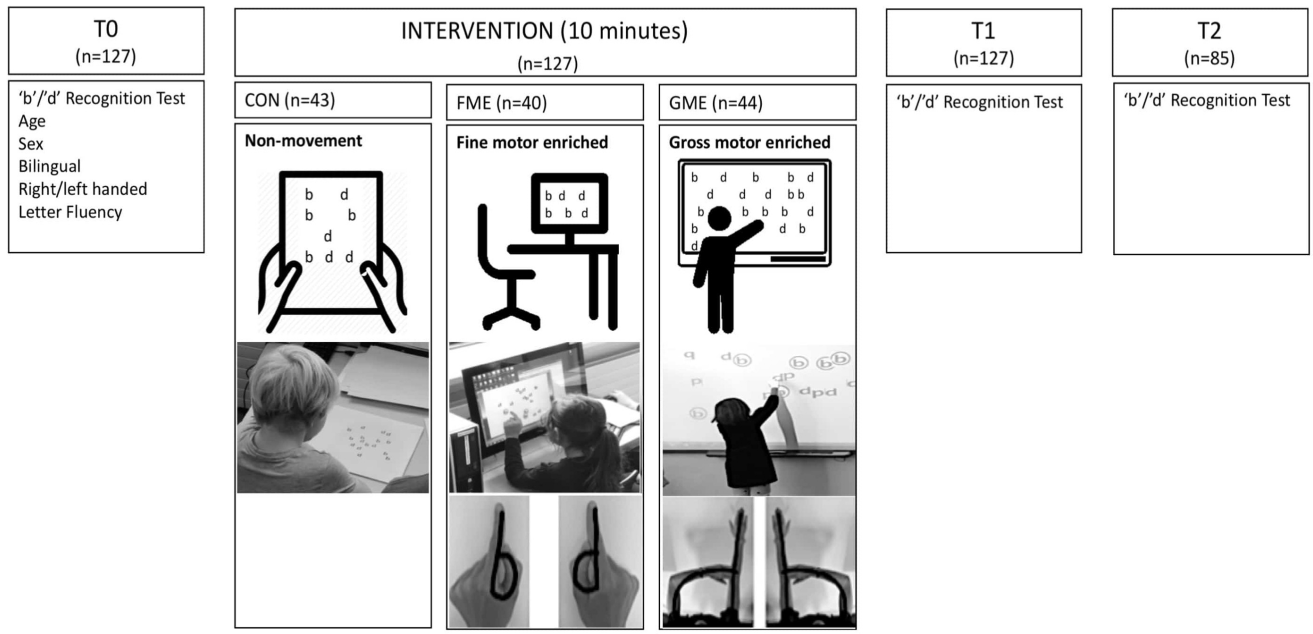

FIGURE 2 | Intervention overview. At T0 a "b"/"d" Recognition Test were performed and participants demographics were collected. All participating children were randomized into three groups: a fine motor-enriched group (FME) and a gross motor-enriched group (GME), that received "b" and "d" activities enriched with gestures as fine and gross motor movements, respectively, and a control group (CON), which received non motor-enriched "b"/"d" teaching. Pictures shows how the children were instructed to use their hands and arms in the FME and GME group. At T1 children performed a "b"/"d" Recognition Test. The next day (after 20–24 h) another "b"/"d" Recognition Test was completed (T2).

20 p/q/m/n) with a stimulus duration of 3000 ms in random order. Prior to the actual test, a familiarization trial of six letters (b, d, p, q, m, and n) was completed, ensuring task compliance. The children were instructed to respond as precise and quickly as possible by pressing the left ctrl-key on keyboard when a "b" appeared on the screen, and the right-arrow-key on the keyboard when a "d" occurred at the laptop screen. Before each letter, "#" appeared in 700 ms as a ready signal. The children's response latency and accuracy were logged. Total numbers correctly identified "b" and "d" and mean reaction time for correct trials were used as an estimate of the children's learning effect of the intervention. All results more than ±2SD from the mean were considered outliers due to misunderstanding and excluded from the analyses (total excluded = 17 trials).

Motivation

To measure the children's intrinsic motivation for the "b" and "d" learning activities the Interest/Enjoyment scale of the Post-Experimental Intrinsic Motivation Inventory (IMI; McAuley et al., 1989) was used in the immediate post evaluation (T1). This questionnaire measures participants' subjective experience related to an activity in an experiment. The Interest/Enjoyment subscale measures participants' interest and enjoyment while performing a given activity and has been found to be a valid self-reported measure of intrinsic motivation (McAuley et al., 1989; Markland and Hardy, 1997). This scale has previously been used in other studies on the motivational effect of integrating physical and learning activities in primary schools (Vazou et al., 2012).

For the present study, the original seven items in the IMI Interest/enjoyment scale were translated into Danish using a translation-backtranslation process (Streiner and Norman, 2008). Because the scale was used in children the original 7-point response-scale was converted to a 4-point scale (1, not true at all; 2, only slightly true; 3, almost true; 4, true).

The investigator read the questions aloud for the children one by one. A mean (see **Table 2**) from the seven questions was calculated for each child and used as a measure for the Intrinsic motivation score.

Statistical Analysis

The statistical analyses were performed in R Studio (R Core Team, Vienna, Austria).

Baseline characteristics were compared between groups using one-way analysis of variance and chi-square tests for categorical measures (bilingual, dominant hand, and sex). One-way ANOVA was used to identify possible group differences in baseline characteristics (Letter Fluency, age, "b"/"d" Recognition Score at T0, number of games and interventions length). If the one-way ANOVA revealed a significant difference ($p < 0.05$) a Tukey single-step adjusted multiple comparison of means was carried out to classify between which groups the differences were observed. Model validation was based upon visual inspection of residual plots and probability plots.

TABLE 2 | Performance at T0, T1, and T2 for the three intervention groups.

Measures	CON			FME			GME		
	T0	T1	T2	T0	T1	T2	T0	T1	T2
General Test Information									
Intervention Length (min)		9.44 ± 0.65			9.40 ± 0.69			9.75 ± 0.85	
Number of Trials		24.61 ± 13.23§			11.10 ± 3.92§			5.02 ± 1.76	
Letter Fluency		66.06 ± 17.19$^{\#\#\#}$			57.0 ± 19.28			55.06 ± 18.96	
Letter recognition (*n* = 127)									
"b"/"d" Score (% Correct Answers)	69.6 ± 43	85.8 ± 25*	89.2 ± 16**,***	73.7 ± 39	93.9 ± 12$^{*,\#}$	96.5 ± 6$^{**,***,\#\#}$	67.6 ± 45	88.8 ± 2*	89.2 ± 18**,***
Reaction time									
Estimated Marginal Means (ms)	948 ± 214.8	875 ± 335.7	823 ± 208.0**	854 ± 214.77	787 ± 237.9*	694 ± 154.5**	850 ± 226.49	780 ± 218.2$^{*,\#}$	704 ± 169.4**
Motivation									
IMQ-Score		3.36 ± 0.51			3.67 ± 0.30§§			3.64 ± 0.35§§	

*Data reported as mean ± SD. "b"/"d" score (% correct answers) are calculated from the statistical model. CON, control group; FME, fine motor-enriched group; GME, gross motor-enriched group. *Indicates a significant difference within group from T0 to T1. **Indicates a significant difference within group from T0 to T2. ***Indicates a significant difference within group from T1 to T2. $^{\#}$Indicates a significant difference in change from T0 to T1 between CON and GME/FME. $^{\#\#}$Indicates a significant difference in change from T0 to T2 between CON and FME. $^{\#\#\#}$Indicates a significant difference between CON and GME in Letter Fluency. § Indicates a significant difference between CON and GME and between FME and GME in amount of trials. §§ Indicates a significant difference between FME and GME compared to CON in IMQ-Score.*

Data from the "b"/"d" Recognition Test were analyzed using generalized linear mixed model with group-time interactions as fixed effects, using R package lme4 (Bates et al., 2015). Since it was possible to score between 0 and 20 for correctly identified letters in the "b"/"d" Recognition Test at timepoint T0 and T1, and 0 and 40 in the T2 test, a general linear mixed model with a binomial distribution fitted the obtained correctly identified letters. The data was analyzed for group x time interactions with CON, FME, GME as groups and time were T0, T1, and T2. To account for the cluster structure and the repeated measures in the data "subjects" and "school" was added as random-effects and "age" as fixed effect, due to the testing period, since children's letter recognition and letter-mirroring are age-dependent (Cornell, 1985).

Ratio Tests were used to reveal group x time interaction effects for accuracy and reaction time for correct "b"/"d" responses. Subsequently, if the test for interaction was significant, pairwise comparisons between delta values (on log odds scale) were used to characterize the interaction effect. To reduce the problem of multiple testing, only relevant model-based specified comparisons were performed including the comparisons of interest (time and group differences) using the *emmeans* R-package.[1] *P*-value adjustment was based upon the Tukey method for comparing a family of three estimates.

Motivation scores were compared between groups by the non-parametric Kruskal-Wallis rank sum test. If the Kruskal–Wallis rank sum test revealed a significant difference ($p < 0.05$) pairwise Wilcoxon rank sum test was used post-hoc to investigate within-group differences. The test does not require the assumption of normal distribution. Pearson correlation coefficient was calculated to see correlation between accuracy in letter recognition and motivation score.

For all tests, a significance level of 0.05 was applied. Data are reported as means ± SD unless otherwise stated.

[1]https://CRAN.R-project.org/package=emmeans

RESULTS

Baseline Characteristics

The one-way-ANOVA revealed no significant between-group differences for the variables age ($p = 0.63$), "b"/"d" recognition ($p = 0.66$), bilingual ($p = 0.97$), dominant hand (R) ($p = 0.83$), or sex ($p = 0.88$) at T0. However, significant between-group differences at T0 was found in Letter Fluency and trial repetitions (**Table 2**). Specifically, CON performed significantly better compared to GME in Letter Fluency ($p = 0.01$) at baseline. Moreover, within the 10 min intervention CON performed more trials compared to GME ($p = 0.04$) and FME performed more trials compared to GME ($p = 0.03$). No correlation was found between the score in letter fluency and children's ability to recognize "b"/"d" at T0, indicating that the score does not influence the main focus in this article. The same was observed with amount of trials and "b"/"d" recognition ($p = 0.06$) at T1 and T2. Therefore, the differences in the amount of trials may not have influenced the ability to recognize letters. Finally, no correlation was observed for correct recognized letters in the "b"/"d" task at all timepoint and time spend on the task ($p > 0.05$).

Performance in Accuracy of "b"/"d" Recognition

Likelihood Ratio Test showed a global significant interaction between time and groups ($p < 0.0005$) for accuracy of "b"/"d" recognition. A significant interaction was found for FME compared to CON from T0 to T1 ($p = 0.008$) and from T0 to T2 ($p < 0.001$). All groups significantly improved accuracy in "b"/"d" recognition from T0 to T1 and from T0 to T2 ($p < 0.0001$) (**Figure 3**). This implies that FME improved children's performance in recognition "b"/"d" more compared to CON from T0 to T1 and T0 to T2.

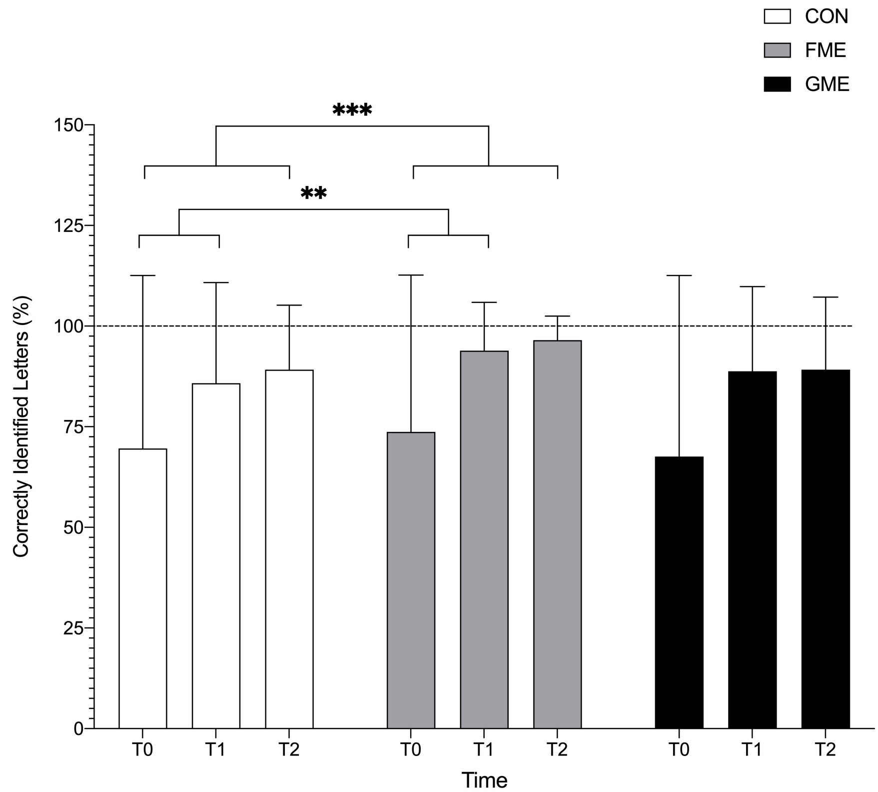

FIGURE 3 | "b"/"d" letter recognition accuracy. Data reported as % correctly identified "b"/"d" letters. The percentage is made upon the statistical model. The line represents 100% correctly identified letters. All groups improved their total correct score (accuracy) to recognize and distinguish the letters "b" and "d" from T0 to T1 ($p < 0.0001$) and T0 to T2 ($p < 0.0001$) (not annotated in the illustration). The fine motor-enriched (FME) intervention had a greater improvement compared to CON from T0 to T1 (p = 0.008) and from T0 to T2 ($p < 0.001$). **, *** indicates significant improvement.

Performance in Reaction Time for "b"/"d" Recognition

Likelihood Ratio Test did not reveal a global significant interaction between time and groups ($p = 0.86$) for reaction time of "b"/"d" recognition. However, planned comparisons revealed that GME and FME improved their mean reaction time significantly from T0 to T1 ($p = 0.001$), see **Figure 4**. A significant interaction was seen for GME compared to CON from T0 to T1 ($p = 0.03$). All three groups improved their mean reaction time significantly from T0 to T2 (CON; $p = 0.007$, FME; $p < 0.001$ and GME; $p < 0.001$).

Despite no global significant interaction between the time and the groups, there were an indication that motor-enriched learning (FME and GME) improved children's mean reaction time for recognition of the letters "b" and "d" from T0 to T1 and from T1 to T2, and a larger improvement in reaction time for GME compared to CON from T0 to T1.

Motivation

Significant differences between groups were found for the Intrinsic Motivation score ($p = 0.003$) using the Kruskall-Wallis rank sum test. Further, pairwise comparisons using Wilcoxon rank sum test showed differences between CON and FME ($p < 0.01$) and CON and GME ($p = 0.01$). Specifically, GME and FME had higher levels of intrinsic motivation for the activities compared to CON. No significant difference was observed between FME and GME ($p > 0.1$). No correlation was found between motivation score and accuracy in "b"/"d" Recognition Test ($p = 0.79$) and between reaction time in "b"/"d" Recognition Test and motivation score ($p = 0.14$).

DISCUSSION

Effect of Fine Motor-Enriched Learning Activities on "b"/"d" Recognition

In this study, a superior positive retention effect of fine motor-enriched letter recognition training was found compared to non motor-enriched training. This result adds some support to the existing literature indicating that motor-enriched activities can enhance entrenchment of children's academically relevant skills.

The improved effect of fine motor-enriched encoding might be a result of combinations of different mechanisms. It is proposed by Chandler and Tricot (2015) that movements integrated into a learning task can possibly influence children's learning through various processes. It is known that attention to learning tasks is highly correlated with achievements, indicating that attention

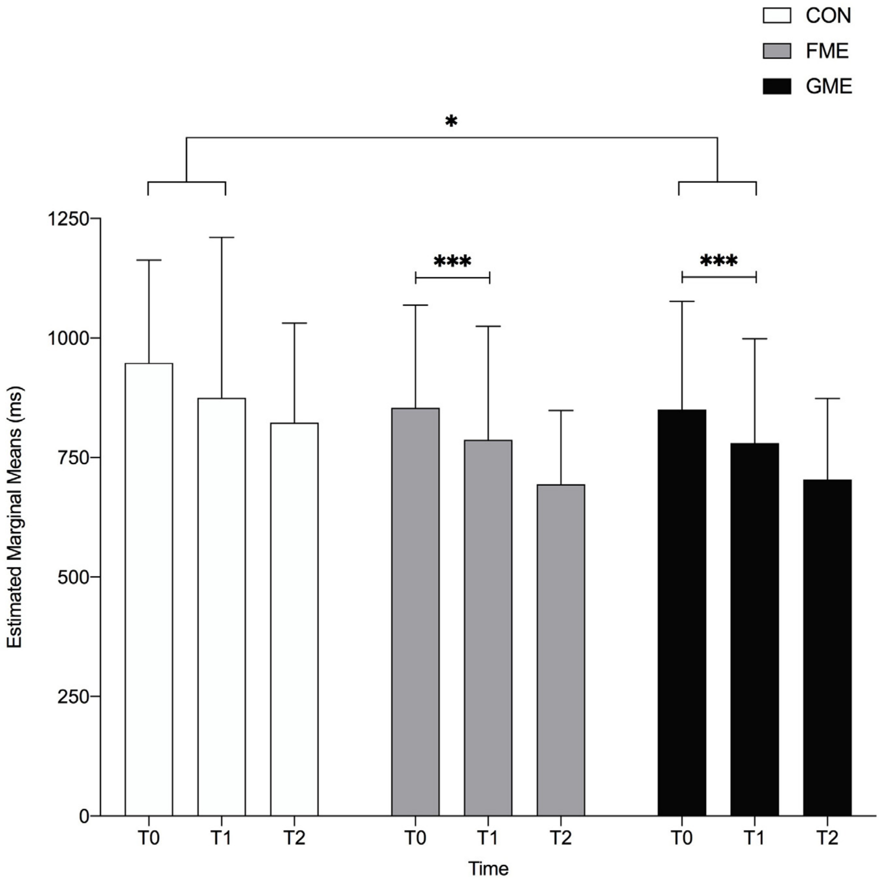

FIGURE 4 | Reaction Time for Correctly Identified "b"/"d." Data reported as estimated marginal means for reaction time (ms). CON, FME and GME improved their mean reaction time from T0 to T2 (p = 0.005, p < 0.001 and p < 0.001). GME and FME improved significantly from T0 to T1 (p = 0.001). The figure illustrates a significant better group-time improvement for GME compared to CON from T0 to T1 (p = 0.03). *, *** indicates significant improvement.

has a beneficial effect on outcomes, and can possibly be one of the reasons why the fine motor activities improve more than the other groups at T2 in letter recognition (Stewart et al., 2007). In this study, an immediate post intervention test (T1) and a one-day retention test (T2) were used to evaluate how well a specific skill was retained after a given time-interval. Based on knowledge of motor skill learning, the delayed retention is a better indicator of motor learning compared to performing right after end of practice (Kantak and Winstein, 2012; Roig et al., 2012). Our results confirmed similar improvements at retention evaluation as previously seen in motor skill learning. The intervention as well as the test are therefore related to conceptual knowledge.

The Difference Between Fine Motor-Enriched Learning and Gross Motor-Enriched Learning in Letter Recognition

Our experiment indicated that a fine motor intervention had a greater positive effect on learning as indexed by correctness in "b"/"d" recognition than a gross motor intervention compared to non motor-enriched training. This is in contrast with previous studies (Beck et al., 2016; Pesce et al., 2016). A potential explanation for the discrepancy could be that the intervention in the present study (i.e., alternating right and left side motor responses) was more similar to the recall situation, which also had right and left side in the motor responses. Another explanation for the improvement in correctness for the fine motor intervention may be provided by the near hand theory. The near hand theory of activating bimodal cells through visual and tactile stimulation to provide spatial attention can explain why the FME group improved significantly more compared to CON from T0→T1 and T1→T2 which GME did not (Cléry et al., 2015; Bufacchi and Iannetti, 2018). The bimodal cells are of great importance for near hand space prioritization and can improve the attention and perception for visual stimuli near the hands. A study by Reed et al. (2006) found that both reaction time and accuracy were improved when stimuli occurred near the hands. In other words, using process selection for a near hand context in cognitive learning like the FME group may improve "b" and "d" recognition more than the non-near hand groups like gross motor movement and the control group (Wassenberg et al., 2005; Goodhew et al., 2015). This effect may help the children in the FME group to sustain attention during the intervention with a more impactful visual and tactile stimulus (Reed et al., 2006).

However, it is important to keep in mind that whereas the control group only used eye movements, the motor-enriched setup additionally involved motor control in relation to verbalization and limb movements. Therefore, we cannot exclude that verbalization also had an influence on the observed improved ability to recognize and distinguish "b"/"d" in the motor-enriched groups relative to the control group. If this would be the case, it should however influence performance in both motor-enriched groups, but the positive effect of motor enrichment was only observed for the FME group. This indicates that our main finding for the FME is not explained by the element of verbalization. It should be recognized as a limitation of the study, that the "b"/"d" Letter Recognition Test which was employed in the present study is a self-developed assessment tool, for which no validation procedure has been performed. Additionally, at one school data was not obtained for the T2 Letter Recognition Test due to practical issues. The generalized linear mixed model does however provide unbiased estimates.

Reaction Time and Motor-Enriched Learning

We did not find any global significant interaction between time and the groups in children's reaction time for letter recognition. However, the present study still found an indication that motor-enriched learning (FME and GME) improved children's mean reaction time for recognition of the letters "b" and "d" from T0 to T1 and a better group-time improvement of reaction time for GME compared to CON from T0 to T1.

In the present study the intervention groups FME and GME had a larger coordinative activity than CON, which might have led to activation of the parts of the brain known to be responsible for mediating functions like attention (cerebellum and prefrontal cortex). Budde et al. (2008) found that 10-min bouts of whole-body coordinative exercise in a group of 13–16-year old enhanced attention and concentration (Budde et al., 2008). A recent study showed that coordinative physical activities improved children's (8–11 years) attention measured with a d2-R test of attention (Gallotta et al., 2015). A study by Schmidt et al. (2016) investigated the effect of a 10-min cognitive challenging task compared to 10 min of physical activities showing that the cognitive challenging task group improved attention measured by a d2-R test, which neither the physical activity group did nor the group that combined the cognitive challenging task and physical activity did (Schmidt et al., 2016). The latter result of the study was unexcepted. The coordinative and challenging activity in especially our GME group may possibly have an influence on the immediate effect to attention leading to a possible explanation of a quicker mean reaction time seen in especially the GME. From the literature, we realize that perceptual movement manipulate the brain, mediate mental representations and memory (Madan and Singhal, 2012). A congruent mental motor stimulation is explained to accelerate the visual recognition (Helbig et al., 2006), which is in line with the present study seeing an improvement in reaction time for FME and GME with significant improvement from T0 to T1 and a significant change for GME compared to CON from T0 to T1.

Intrinsic Motivation

Intrinsic motivation is impelled by many factors and is an important component to facilitate in teaching (Guay et al., 2010). A higher level of intrinsic motivation for the intervention activity was seen in motor-enriched groups compared to CON, indicating that motor-enriched teaching is more intrinsically motivating. No difference was seen between the FME and the GME. This finding is in agreement with Vazou and colleagues who found higher levels of enjoyment (a construct very similar to and closely related to intrinsic motivation) among pupils, after incorporating a 10-min single bout of acute moderate to vigorous physical activity in math lessons and also showed an improvement in reaction time at a standardized flanker task (Vazou and Smiley-Oyen, 2014). Our result on intrinsic motivation is also in line with an experimental study on having physical activity breaks when teaching different academic subjects which showed that integration of physical activity lessons were more intrinsically motivating to school children (Vazou et al., 2012). It is well established that intrinsically motivated behaviors are positively related to children's psychological well-being, high-quality learning, academic achievement, and future academic success (Linnenbrink and Pintrich, 2002; Lepper et al., 2005; Burton et al., 2006). It is shown that intrinsic motivation is correlated with academic achievement, long-term performance, and wellbeing in children (Gottfried, 1990; Goldberg and Cornell, 1998; Broussard and Garrison, 2004). Therefore, the higher intrinsic motivation for the motor-enriched activities in the intervention groups FME and GME could have impacted both the acquisition of learning "b" and "d" in the intervention and the "b"/"d" letter testing session and thereby the outcome. However, several factors such as participant involvement, self-determination, the academic level, and relevance of the activity, all influence participants' motivation (Deci and Ryan, 2002; Bugge et al., 2015).

CONCLUSION

Children's participation in 10 min of fine motor-enriched activities improved their ability to recognize and distinguish "b" and "d" compared to children who performed non motor-enriched activities. In general, improvement in letter recognition were seen in the motor-enriched activities compared to control. Both fine motor-enriched activities and gross motor-enriched activities resulted in a positive effect on children's intrinsic motivation for performing the activities.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/Supplementary Material.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Local Ethical Committee at UCPH. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

LD, JW, AG, MP, AB, JL-J, and AM designed the experiment. LD, AG, JW, AB, and SE collected the data. LD and SE conducted the required data analysis. GN conducted the analysis for the motivation parameters. LD drafted the first version of the manuscript. All authors contributed to drafting the manuscript and approved the final version of the manuscript.

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Active Learning Norwegian Preschool(er)s (ACTNOW) – Design of a Cluster Randomized Controlled Trial of Staff Professional Development to Promote Physical Activity, Motor Skills, and Cognition in Preschoolers

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Introduction: There is a dearth of high-quality evidence on effective, sustainable, and scalable interventions to increase physical activity (PA) and concomitant outcomes in preschoolers. Specifically, there is a need to better understand how the preschool context can be used to increase various types of physically active play to promote holistic child development. The implementation of such interventions requires highly competent preschool staffs, however, the competence in promoting PA is often low. The main aim of the ACTNOW study is therefore to investigate the effects of professional development for preschool staffs on child PA and developmental outcomes.

Methods: The study will be conducted in Norway 2019–2022 and is designed as a two-arm (intervention, control) cluster randomized controlled trial (RCT) with 7- and 18-months follow-ups. We aim to recruit 60 preschools and 1,200 3- to 5-years-old children to provide sufficient power to detect effect sizes (ESs) between 0.20 and 0.30. The intervention is nested within two levels: the preschool and the child. Central to the ACTNOW intervention are opportunities for children to engage in a variety of "enriched," meaningful, and enjoyable physically active play that supports the development of the whole child. To this end, the main intervention is a 7-month professional development/education module for preschool staff, aimed to provide them with the necessary capacity to deliver four core PA components to the children (moderate-to-vigorous PA, motor-challenging PA, cognitively engaging play, and physically active learning). We will include a range of child-level outcomes, including PA, physical fitness, adiposity, motor skills, socioemotional health, self-regulation, executive function, and learning. At the preschool level, we will describe implementation and adaptation processes using quantitative and qualitative data.

Discussion: Professional development of staff and a whole-child approach that integrates PA with cognitively engaging play and learning activities in the preschool setting may provide a feasible vehicle to enhance both physical and cognitive development in young children. ACTNOW is designed to test this hypothesis to provide a sustainable way to build human capital and provide an early solution to lifelong public health and developmental challenges.

Clinical Trial Registration: www.ClinicalTrials.gov identifier NCT04048967.

Keywords: preschool, public health, professional development, enriched physical activity, child development, motor competence, cognition, integration

INTRODUCTION

Giving every child the best start in life should be the highest priority to address social inequalities and to improve population health, laying the foundation for equitable development of human capital and life opportunities (Ministry of Health and Care Services, 2007; Marmot, 2010). Physical activity (PA) provides young children opportunities for developing their physical, motor, socioemotional, and cognitive skills. PA plays a key role in preventing non-communicable diseases and at an early age provides a foundation for optimal health and development that represents a critical investment in children's development of human capital (Bailey et al., 2013; Carson et al., 2017). Yet, there are growing concerns regarding low PA levels among children and youth, including preschoolers (Bornstein et al., 2011; Driediger et al., 2018; Truelove et al., 2018; Nilsen et al., 2019c). The preschool (97% coverage among 3- to 5-years-old in Norway) and school settings are optimally suited to reach most children, irrespective of social background, with initiatives to increase PA levels and improve health and development. Since interventions before school age provide the most cost-effective solutions (Doyle et al., 2009), there is a need for broad, scalable interventions to increase PA in preschoolers. However, the existing interventions have lacked effectiveness (Finch et al., 2016; Wick et al., 2017), and only a few studies with suboptimal designs have investigated cognitive outcomes (Carson et al., 2016). As a result, evidence is insufficient to shape policy. *In response, the ACTNOW study has two main research rationales. First, to address the lack of evidence of effective and sustainable interventions to increase PA and concomitant outcomes in preschoolers, including evidence on how, why, and for whom interventions may work or not. Second, to provide evidence about the effect of PA on young children's mental health and cognitive development, including measures of socioemotional health, self-regulation, executive function, and learning.*

Overwhelming evidence shows that PA promotes physical health and reduces the risk of non-communicable diseases in adults (Pedersen and Saltin, 2015) and risk factors for non-communicable diseases in children (Poitras et al., 2016). There is also increasing evidence that PA beneficially affects brain health, cognition, and learning in children (Donnelly et al., 2016; Alvarez-Bueno et al., 2017a,b; Norris et al., 2019). Recent systematic reviews have shown positive effects of PA on cognitive outcomes in 3- to 18-years-old, but effects are generally small and inconclusive (mean standardized ESs 0.11-0.30 across cognition and academic outcomes) (Alvarez-Bueno et al., 2017a,b; Singh et al., 2019). However, cognition and learning outcomes are rarely reported in children under 6 years of age (Norris et al., 2019; Singh et al., 2019), a period during which brain development is greatest (Thompson and Nelson, 2001) and the brain is most susceptible to stimuli. In addition, the existing studies are methodologically weak (Carson et al., 2016; Norris et al., 2019; Singh et al., 2019). Consider a recent systematic review in 0- to 5-years-old (Carson et al., 2016); of the five experimental studies included, no studies were rated high quality, no studies investigating chronic effects used a randomized controlled design, and sample sizes were low (10-94 participants). Thus, there is an urgent need for high-quality, rigorous research, with large samples, that examines how PA affects cognitive development in young children (Norris et al., 2019; Singh et al., 2019).

Several causal mechanisms have been proposed to explain how PA affects children's cognitive development through altered brain structure and function (Best, 2010; Meeusen et al., 2018). Mechanisms may be impacted by the quantity or dose (intensity, duration, and/or frequency) of PA (Howie et al., 2015; Howie and Pate, 2018) and by the type or quality of PA due to the cognitive or coordinative demands inherent in PA (Pesce, 2012; Diamond, 2015; Pesce et al., 2018). Qualitative features may relate to motor challenges (adapting to new or complex movement patterns) (Diamond, 2000; Guadagnoli and Lee, 2004; van der Fels et al., 2015), the complexity of the PA context (structured games or active play demanding executive functions) (Chang et al., 2013; Schmidt et al., 2015; Tomporowski et al., 2015), and/or PA integrated with other learning activities (physically active learning) (Mullender-Wijnsma et al., 2016; Mavilidi et al., 2017, 2018a). Evidence from the latter line of research, focusing on the qualitative features of PA, points to the importance of children's mindful engagement in the PA to optimally stimulate their socioemotional and cognitive development and learning. Within this line of research, PA should be "enriched" to provide children with physical activities that are cognitively challenging, emotionally loaded, and socially engaging (Pesce et al., 2018). Enrichment of PA through manipulation of the task and/or environment requires goal-directed behavior underpinned by higher-order cognitive control mechanisms or executive functions (Best, 2010). The joint focus on motor competence and cognition (Pesce, 2012; Diamond, 2015; Pesce et al., 2018) bridges research targeting the effect of PA for both physical and mental developmental outcomes. These perspectives substantially broaden the traditional focus on PA: moving away from the predominant attention to the intensity and metabolic demands of PA to also include the use of mindful PA. Given this framework, more high-quality research is needed to investigate how these foci and features of various activities can be integrated to jointly impact children's physical fitness, motor competence, executive function, socioemotional development, self-regulation, and learning.

Studies of interventions to increase objectively measured PA (Finch et al., 2016) and motor competence (Wick et al., 2017) in children aged 0-6 years have shown small to moderate effects. These are disappointing and driven, in part, by poor study quality (Wick et al., 2017) and the challenge of translating well-controlled efficacy trials to effectiveness studies in preschool settings. Separate meta-analyses by Finch et al. (2016, 15 studies investigating PA) and Wick et al. (2017, 26 studies investigating motor competence) revealed that efficacy trials have the potential to significantly improve PA and motor competence in young children, whereas effectiveness trials – performed under real-world conditions – are not beneficial. Specifically, short-term interventions and interventions delivered by external "experts" were effective (mean standardized ESs 0.58-1.54), whereas long-term interventions and interventions delivered by preschool staff were ineffective (ESs 0.07-0.41). Similar effects are shown for cognitive outcomes across studies with preschool- and school-aged children (Norris et al., 2019). These findings show that the benefit of PA is tangible, but there exist no effective, scalable solutions to increase PA in the actual preschool setting, which provides limited direction for policymakers and practitioners.

Promoting PA in an enjoyable and motivating manner, with a focus on moderate-to-vigorous PA (MVPA) that stimulates motor competence and integrates with other preschool activities and objectives, requires great effort and thus competent and motivated preschool directors and staff. However, previous preschool studies have provided minimal teacher training and support. Among the five high-quality studies reviewed by Wick et al. (2017) where the intervention was delivered by the staff, and among the five relevant studies deemed pragmatic in the review by Finch et al. (2016), studies provided only one to five workshops along with some follow-up sessions. More recent studies, still showing equivocal effects, offer similar low amounts of teacher training (Goldfield et al., 2016; Jones et al., 2016; Adamo et al., 2017; Tucker et al., 2017). These are contrasted with examples such as the *Study of Health and Activity in Preschool Environments* (SHAPES, United States), *Motor Skills in PreSchool* (MiPS, Denmark), and *Joy of Moving* (Italy), all of which established stronger relationships between interventionists and staff through teacher training, workshops, and follow-ups than most other studies (Pfeiffer et al., 2013; Howie et al., 2014; Pesce et al., 2016; Hestbaek et al., 2017). The lack of staff professional development is concerning because there is a well-known challenge of a low competence level in the preschool sector internationally. In Norway, <50% of the preschool staff are certified teachers (The Norwegian Directorate of Education, 2016), and there is a specific lack of staff's competence in promoting PA, and probably more so in promoting PA aimed to affect motor skills, cognition, and learning. As a result, we argue that much of the failure to support preschool interventions is due to the lack of director and staff training. Moreover, well-trained staff can become partners in the co-creation of the specific components of the intervention as applied to their preschool, along with ongoing efforts to evaluate and continuously improve the intervention. That is, not only must the staff be sufficiently trained to implement the program, they must be sufficiently trained to modify and improve on the intervention to support long-term sustainability. Finally, randomized controlled trials (RCTs) are unable to explain why an intervention may work in a particular context or for a particular group of participants. Thus, examining the ways an intervention is put into practice and delivered to its participants is fundamental to avoid an inaccurate attribution of the cause(s) of results (Lendrum and Humphrey, 2012; Durlak, 2016; Humphrey et al., 2018). It is well documented that implementing interventions into the school setting is complex and challenging for a variety of reasons (Lendrum and Humphrey, 2012), but less is known about the preschool setting. Thus, a thorough description of the implementation and evaluation of these processes should be included in future trials as a prerequisite to scaling interventions in the real world (Howie et al., 2014; Reis et al., 2016).

Research Gap and Research Questions

There is an urgent need for large, high-quality PA intervention studies in preschool that can demonstrate effectiveness in a dynamic and complex real-world setting and that are scalable to broader national and international contexts. Therefore, the aim of this study is to investigate the effects of an education module, which is designed to create preschool staff who are highly competent in promoting various aspects of physically active play that, in combination, have the potential to simultaneously affect various developmental and learning outcomes, underpinning a whole-child approach. If effective, ACTNOW will provide further evidence of the efficiency, acceptability, and feasibility of the preschool setting in building human capital and providing an early solution to lifelong public health and developmental challenges.

Two main research questions will be tested using both quantitative and qualitative methods, applied to both the child and preschool levels:

1. How does the intervention affect children's PA, physical fitness, motor competence, socioemotional health, self-regulation, executive functions, and learning?
2. How does the intervention interact with different preschool contexts to produce various individual and organizational outcomes?

METHODS AND ANALYSIS

Design

The research questions will be investigated using a two-arm (intervention; control) cluster RCT with randomization at the preschool level, including 7- and 18-months follow-ups. Consistent with recommendations from implementation research in the school setting (Lendrum and Humphrey, 2012; Durlak, 2016), ACTNOW will include strong involvement from preschool owners and staff to provide broad support and anchor the project in the preschool sector. Thus, we aim to combine a large-scale experimental study with intervention co-creation and a continuous improvement effort in this sector. We will achieve this combination by making a compromise between the standardization needed in an experimental trial and the adaptations and flexibility needed for the intervention to be accepted, internalized, and further developed by the preschools. This approach is consistent with favorable effects of user adaptation of interventions (Søvik et al., 2017) and will hopefully improve staff participation in the professional development and thus effectiveness of the intervention over previous similar interventions (Finch et al., 2016; Pesce et al., 2016; Wick et al., 2017). This approach overcomes a common criticism of clinical trials as it increases the value for later scaling and dissemination to the real-world settings. In this way, we aim to create sustainable solutions for improved child development and public health. Thus, the intervention's development, implementation, and evaluation are framed within a "realist RCT" approach (Bonell et al., 2012) providing the rationale for a thorough process evaluation of the study.

ACTNOW is registered in the ClinicalTrials.gov database with identification number NCT04048967 (August 7 2019)[1] prior to recruiting any participants.

Intervention and Theoretical Framework

The intervention is framed within a socioecological model (McLeroy et al., 1988), placing the preschool as an influential factor for children's health and development. The intervention is nested within two levels (**Figure 1**); the *preschool* and the *child*, of which will be implemented concurrently. On the child level, the intervention is composed of four core components of various types of PA. Given this complexity and the challenge of low staff qualifications to implement PA, the 7-month professional development *Active Learning Preschoolers* will be offered to preschool directors and teachers during Year 1. The professional development is structured as a 15-credit continuing education module that provide staff the opportunity to achieve credits for

[1] https://clinicaltrials.gov/ct2/show/NCT04048967?term=actnow&rank=1

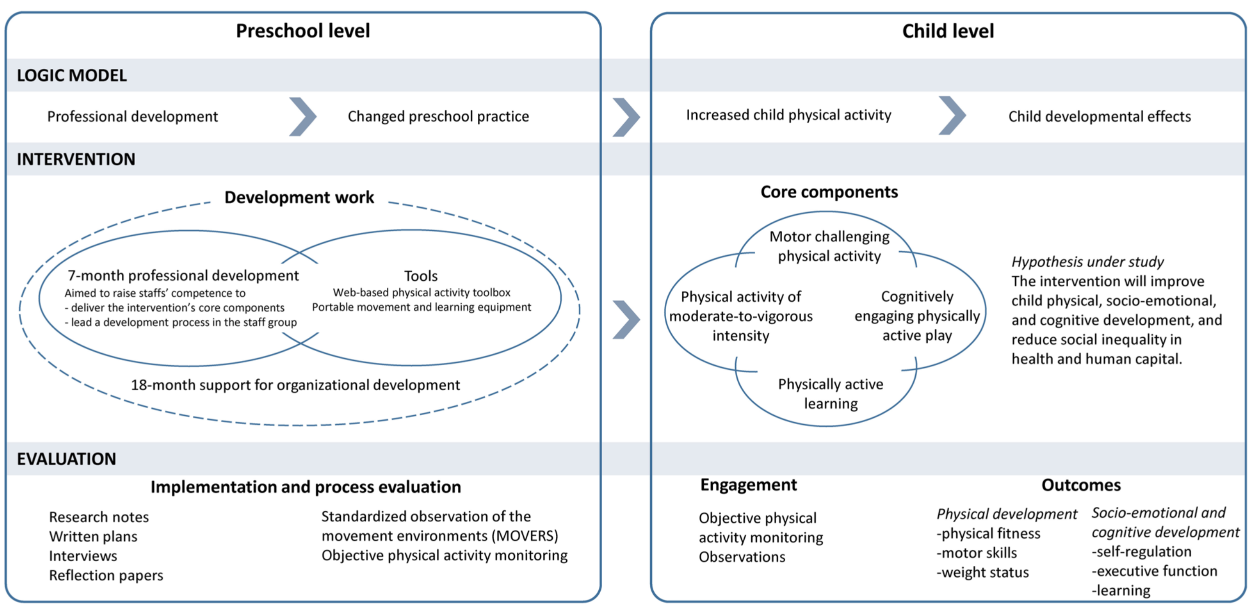

FIGURE 1 | The two-level intervention model.

their efforts. Moreover, the preschools will be equipped with tools to support the intervention implementation, including a web-based PA toolbox (an ideas bank of child activities framed within the four core intervention components) and portable movement and learning equipment, providing a basis for implementing the new PAs. Finally, preschools will be offered continuous support over the 18-month intervention period to facilitate the intervention implementation (Years 1 and 2). The study is based on the logic model that the professional development, additional resources, and support will change preschool practices, which will in turn increase and improve children's PA opportunities that will cause child developmental effects. Thus, the aim of the preschool level intervention is to provide preschool staff the necessary expertise, resources, and capacity to intervene on the child level. Researchers will not directly deliver the intervention at the child level.

At both the *preschool* and the *child* levels, we seek to create a mastery-motivational climate as well as an autonomy supportive climate guided by the Achievement Goal Theory (AGT) (Ames, 1992) and Self-Determination Theory (SDT) (Ryan and Deci, 2000). Together, these two perspectives are hypothesized to provide social-contextual conditions expected to facilitate learning, growth, and development among preschool directors, teachers, as well as the children. A mastery climate emphasizes effort, progress, and optimal challenges facilitating the intrinsic value of learning. According to AGT, creating a mastery climate will help influence a person's beliefs, attributions, affect, and goal of action. Specifically, creating a mastery-oriented climate will help individuals to relate effort to mastery and success, to take interest in developing new skills and improve their level of competence, and evaluate their achievement by using self-referenced standards (Ames, 1992). According to the SDT perspective, an autonomy supportive climate, as well as a structure supportive and a relatedness supportive climate, will provide social-contextual conditions that help stimulate intrinsic motivation, self-regulation, and socioemotional health through three basic psychological needs: competence, relatedness, and autonomy (Ryan and Deci, 2000). As such, if the intervention succeeds across both staff and children in fostering the above social-contextual conditions emanating from AGT and SDT, it is expected that staff and consequently children may enhance their intrinsic motivation for learning, persist in their respective activities, and have creativity and performance, as well as increase their self-esteem and general socioemotional health.

To create a mastery-motivational climate at both the preschool and child levels, we will use the instructional strategies put forward by Ames (1992, p.267): (a) provide staff and children with tasks that are meaningful, novel, varied, and that offer reasonable (personal) challenge and focus on self-referenced goals; (b) focus on individual improvement, progress and mastery, value effort, and encourage viewing mistakes as part of learning. AGT has shown to be effective in intervention studies aiming to improve MVPA and motor skills in preschool children (Robinson et al., 2016, 2018; Palmer et al., 2017). Further, grounded in SDT: create an autonomy-, structure-, and relatedness-supportive climate that includes the staff and children in their respective processes of learning and development by allowing for influence in decision-making, giving opportunities to develop responsibility and independence, and structuring their learning and play activities, as well as creating a sense of group belongingness (Ryan and Deci, 2000).

The Child Level

The intervention at the child level is derived from theory and evidence relating to the beneficial effects of PA on physical, socioemotional, and cognitive development. Central to the ACTNOW intervention is opportunities for children to engage in a variety of meaningful and joyful *physically active play* activities that support the development of the whole child.

The rationale for each of the four core components in the intervention model is based on theory and evidence from different fields of research, including physiological, psychological, and phenomenological perspectives, including both acute and chronic effects of PA, as illustrated in the inner flower in the diagram (**Figure 2**). Essentially, the left part of the intervention model is focused on the quantitative characteristics of PA, such as the dose (duration, intensity, and/or frequency) of PA. The right part of the model focuses on the qualitative characteristics of the intervention, with emphasis on the type and mode of PA. By the integration of the four core components, we aim to provide children opportunities to increase MVPA across a wide range of motor competencies to enhance development, cognitively engaging play, and physically active learning.

Modes of delivery

The intervention will be delivered by the staff through the use of a wide range of physically active play (**Table 1**); from child-initiated and directed free play at the one end, to adult-initiated child-directed guided play and adult-directed and initiated structured teacher-led PA at the other end (Deena Skolnick et al., 2015). In accordance with our theoretical frameworks for the intervention, guided play gives the child autonomy to decide what to do, what to explore, and how to do it. Hence, the role of the teachers when using guided play is to provide children with an enriched PA environment and scaffold the children's initiatives and actions (Deena Skolnick et al., 2015; Archer and Siraj, 2017). Such an approach can extend children's understanding of, for example, spatial terms (e.g., over, behind, next to), shapes, numbers, and increase their movement vocabulary (Deena Skolnick et al., 2015; Archer and Siraj, 2017). Furthermore, preschool teachers will be encouraged to take part in the activities and model ways of moving, as well as scaffolding children in need to overcome physical-motor barriers to ensure that *all* of them develop the necessary competencies to be included in and master the activities (Archer and Siraj, 2017). Reaching every child is a primary goal since PA levels and motor competencies vary considerably among children, and preschools might favor PA in some groups of children more than others (Nilsen et al., 2019b,c).

Environment and context

The intervention activities will take place indoors and outdoors, both within and outside of the preschool area (e.g., using a nearby forest, beach, park, playground, etc.). Because more time spent outdoors is associated with increased PA (Bingham et al., 2016;

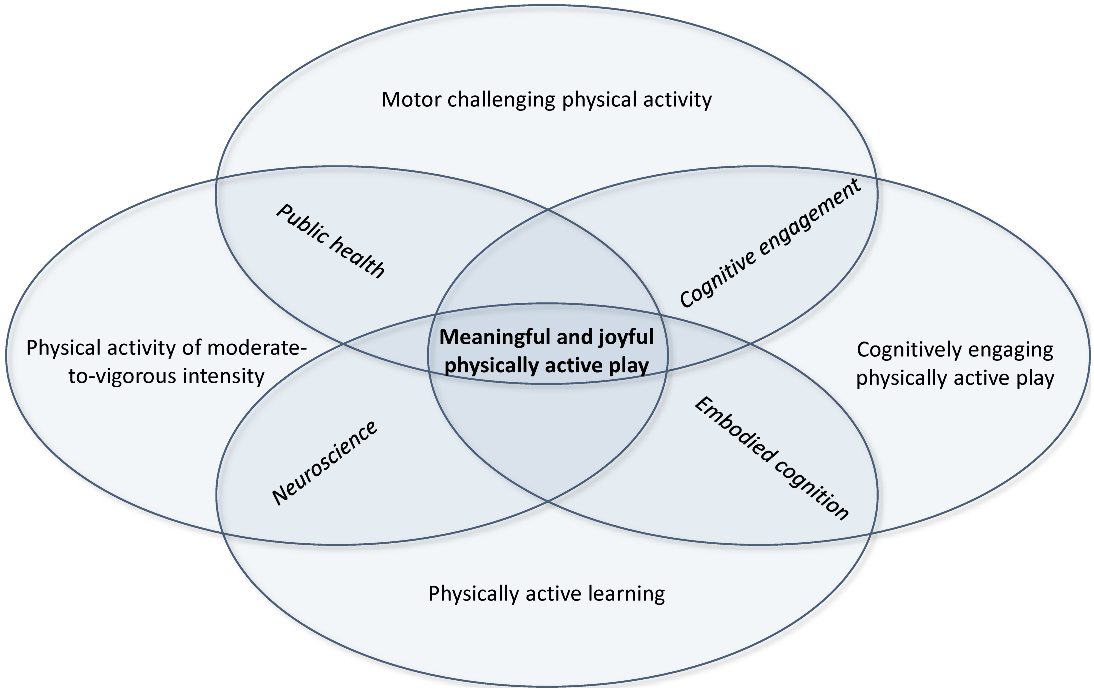

FIGURE 2 | The intervention model at the child level.

TABLE 1 | The four core components of the intervention (child level).

Component	Delivery	Dose
Physical activity of moderate-to-vigorous intensity	The MVPA component will focus on promoting energetic play using gross motor activities involving the whole body, such as running, skipping, and jumping, through: • Short bouts of vigorous PA (e.g., spurts of running). This activity pattern builds on the natural pattern of PA in the early years (Ruiz et al., 2018). • Breaking up outdoor free play to promote structured adult-led MVPA. Because children are most active at the beginning of a play session, a boost with adult-led activity will potentially increase the level of MVPA (Greever et al., 2015).	60 min/day
Motor challenging PA	The motor challenge component will focus on physically active play and movements that challenge children's motor competencies through: • Various gross motor activities across all motor competence domains; locomotion, object control, and balance. • Manipulation of tasks and environment to meet the children's optimal challenge point (Guadagnoli and Lee, 2004).	90 min/week
Cognitively engaging physically active play	The cognitively engaging component will focus on physical active play requiring mental engagement through: • Physically active play that taps the executive functions, such as stop tasks, memory tasks, shifting tasks, and creativity tasks (Tomporowski et al., 2015). • Modified group games requiring executive functions, for example, ball games and tag games (Tomporowski et al., 2015).	90 min/week
Physically active learning	The physically active learning component will focus on PA integrated with learning activities through: • Non-task-relevant MVPA that incorporates academic content from the Framework Plan (Norwegian Directorate for Education and Training, 2017). • Task-relevant PA integrated with academic content from the Framework Plan (Norwegian Directorate for Education and Training, 2017).	90 min/week

Driediger et al., 2018), and better cognitive and behavioral development (Ulset et al., 2017), preschools will be encouraged to spend ample time outdoors each day. Through the use of various environments, children will have access to play areas with a variety of surfaces (e.g., floor, grass, sand, bark, mud, dry, wet, snow, ice, etc.) and terrain (flat, hilly, rocks, trees, etc.) to support the variability of practice and optimal stimuli of motor and cognitive development (Pesce et al., 2019). The environment, both inside and outside, will be enriched by portable equipment to encourage various movements, including hula-hoops, balls of different sizes and weights, bean bags, sensory slices, cones, and hurdles. Such portable play equipment has been shown to increase MVPA (Driediger et al., 2018; Määttä et al., 2019). Furthermore, equipment such as dice, letters, shapes, and pictures will be provided to incorporate learning goals through physically active play.

Most of the intervention activities will take place in groups of children, facilitating interaction between peers and with staff. Socially oriented physically active play and games are important for the development of socioemotional competence and hence friendships in the early years. Furthermore, physically active play can affect social connectedness and a sense of belonging (Bailey, 2017). Therefore, promotion of such activities is especially important for children showing the least developed social skills (Bailey, 2017).

The "physical activity of moderate-to-vigorous intensity" component

The specific amount of PA needed for optimal development and health in the early years is unclear (Timmons et al., 2012; Carson et al., 2017). More intense PA appears to be most favorable to health (Carson et al., 2017), and cognitive and psychosocial development (McNeill et al., 2018). In Norway and internationally, it is recommended that young children spend at least 60 min/day in MVPA (Tetens et al., 2014; World Health Organization [WHO], 2019). There is general concern about low PA levels internationally (Bornstein et al., 2011; Driediger et al., 2018; Truelove et al., 2018), and recent evidence shows that only 55% of 3- to 5-years-old in Norway achieve this amount of MVPA (Nilsen et al., 2019c).

Beyond physical health, a sufficient dose of PA is also hypothesized to be of importance for cognition, with executive function being the most promising outcome (Tomporowski et al., 2008). The general physiological and metabolic mechanisms that are related to aerobic fitness (Best, 2010) are suggested as pathways for how PA affects executive functions (The Aerobic Fitness Hypothesis) (Howie et al., 2015; Howie and Pate, 2018). Research with 9- to 10-years-old children has shown that higher-fit children have better executive function, greater activity in brain regions important for attention and memory, and a positive change in gray matter volume in brain regions implicated in learning (Chaddock et al., 2011). In preschool children, Niederer et al. (2011) found that aerobic fitness predicted attention 9 months later, but such relationships are scarcely investigated in young children.

The "Motor challenging physical activity" component

Learning to move is essential for PA, and during the early years, children acquire competence in diverse fundamental movement skills, such as locomotion and object control (Stodden et al., 2008). Motor competence has been suggested to be a primary underlying mechanism that promotes engagement in PA, both acutely and over the long-term. A conceptual model by Stodden et al. (2008) proposes a synergistic relationship among motor competence, perceived motor competence, PA, physical fitness, and weight status. During the early years, the child's perception of their motor competence is especially important, as children with high perceived motor competence are more persistent and engaged in various activities. Importantly, their perceived motor competence might be weakly correlated to their actual motor competence (Stodden et al., 2008). As such, an intervention aiming to improve motor competence might benefit from building children's perceptions of their motor competence. Moreover, both AGT and SDT emphasize perceived competence as an important psychological factor (Robinson et al., 2015), which may act as a mediator between actual motor competence and actual/future PA, as well as various developmental outcomes. Robinson et al. (2015) reviewed the proposed links in the conceptual model by Stodden et al. (2008) and concluded that motor competence and PA are weakly to moderately associated in early and middle childhood. This is consistent with results from a large Norwegian study in preschoolers, which extends these results by showing that the association pattern between PA and motor competence is characterized particularly by vigorous intensities (Nilsen et al., 2019a).

Importantly, motor competence will likely not be optimally stimulated through naturally occurring behaviors and thus needs to be taught (Stodden et al., 2008; Robinson et al., 2016). Furthermore, to optimally promote motor competence, it is important to provide challenging activities that keep the children on a positive trajectory of learning and maximize motivation and engagement (Robinson et al., 2015). Consistent with the Challenge Point Framework (Guadagnoli and Lee, 2004), the ACTNOW intervention seeks to adapt intervention activities that are developmentally appropriate and individually adapted in order to meet each child's optimal challenge point.

Providing children with challenging motor tasks may also be a viable way to affect their executive functions, through increased cognitive engagement (Best, 2010). Motor tasks that are novel or not automatized require the involvement of executive functions (Diamond, 2000; Guadagnoli and Lee, 2004; van der Fels et al., 2015; Pesce et al., 2019), and an interrelation between the brain structures important for motor skills (cerebellum) and the structures important for executive functions (the prefrontal cortex) has been described (Diamond, 2000). The interrelation between these structures is evident by their co-activation during motor and cognitive tasks, their similar developmental timetable, and their common underlying processes such as, for example, planning (Diamond, 2000; Roebers et al., 2014; van der Fels et al., 2015). As such, practicing challenging motor tasks may lead to specific adaptation in brain areas (prefrontal cortex) that support executive functions (Best, 2010). The importance of meeting children's optimal challenge point to affect their executive functions has been highlighted in the literature (Pesce et al., 2013, 2019; Tomporowski et al., 2015; Diamond and Ling, 2016). Some evidence also exists for added value of motor skill tasks to executive functions beyond the effects of MVPA (Chang et al., 2013; Koutsandreou et al., 2016).

The "Cognitively engaging physically active play" component

Increasing the complexity of the PA context through structured games or active play, which engage core executive functions, is a viable way to increase the cognitive demands of PA and hence promote executive functions (Best, 2010; Pesce, 2012;

Tomporowski et al., 2015). It has been suggested that engaging executive functions through play can confer benefits to other domains where executive functions are needed (Best, 2010). In group games, the learning environment is in constant change, and the child needs to adapt his/her movement in relation to these dynamic changes. In doing so, the child uses his/her executive functions.

Furthermore, manipulation of activities can increase demands on executive functions. Such manipulation is important, as executive functions need to be continuously challenged in order to be improved (Tomporowski et al., 2015; Diamond and Ling, 2016). In regard to the optimal Challenge Point Framework (Guadagnoli and Lee, 2004), the cognitive load of an activity needs to be tailored to each child. Previous research has shown that children with different abilities may benefit from different activities. For example, Pesce et al. (2013) showed that a cognitively enriched PA program facilitated development of attention in typically developing children (aged 5–10) but not in children with Developmental Coordination Disorder.

The "Physically active learning" component

The physically active learning component will integrate PA with different learning areas in *The Norwegian Framework Plan for Kindergartens* (Norwegian Directorate for Education and Training, 2017). Learning areas in the Framework plan are: (*1) communication, language, and text; (2) body, movement, food, and health; (3) art, culture, and creativity; (4) nature, environment, and technology; (5) quantity, spaces, and shapes; (6) ethics, religion, and philosophy; and (7) local community and society* (Norwegian Directorate for Education and Training, 2017). The physically active learning component derives from the research fields of both acute exercise and embodied cognition. From the exercise and cognition field, the physiological effects of acute PA might facilitate the learning process of academic content by increased arousal. For example, acute PA of a sufficient intensity/dose can raise the concentration of neurotransmitters and cortisol to levels that have positive effects on cognition (McMorris and Hale, 2012; Koutsandréou et al., 2016). Bouts of PA with academic content have shown improved on-task behavior in school settings (Mahar et al., 2006; Grieco et al., 2016). As such, gross motor MVPA coupled with academic content will be promoted in the intervention.

From the perspective of embodied cognition, the relevance of PA for the academic content is of importance. Gesturing or PA that are tightly coupled to the academic content might off-load demands on working memory during learning, through experiencing complementary content through several senses that use different memory traces. As such, it is hypothesized that the learning trace will be of higher quality, and as such better learned (Mavilidi et al., 2018b). Some of the intervention activities will be tightly coupled to the learning content, for example, by forming letters, shapes, and figures with the children's bodies. Several studies in preschool children have successfully used task-relevant PA to learn academic content in, for example, language/literacy (Kirk et al., 2014; Mavilidi et al., 2015), numeracy (Schmidt et al., 2015), and science (Mavilidi et al., 2017).

The Preschool Level

The staff professional development is described in **Table 2**. As described above, a flexible intervention that includes co-creation and continual improvement with staff is recommended to facilitate sustainable change in educational contexts (Routen et al., 2017). The ACTNOW intervention will therefore be adjusted to the needs and resources in each preschool. Alongside the involvement of directors and teachers in the professional development, the research group will work in partnership with each preschool and its entire staff to ensure support and commitment, not only among those enrolled in the professional development. As recommended by the literature on health promotion assessment and interweaving (Springer et al., 2017), the process among staff will begin by involving all in an analysis of the preschool's existing PA policies and practices as well as an assessment of staff and children's needs and resources related to PA, and thus their readiness for change. Based on the assessment, staff will develop a written PA policy with set priorities and objectives, which will incorporate both intervention levels, including the four core components for children. Depending on each preschool's current practice, the elements of the intervention will add to, extend, and/or integrate with and improve existing activities in line with the Theory of Expanded, Extended, and Enhanced Opportunities (Beets et al., 2016), which corresponds with concepts of organizational learning (Nonaka, 1994; Wells, 1999; Moilanen, 2005). In collaboration with the researchers, the next phase will involve developing strategies for the implementation and integration of the new policy and practices into the preschool's daily practice (Fitzgerald and Theilheimer, 2013; Heikka et al., 2019). The final phase will consist of monitoring and evaluation, revision, and learning. Given that the principal/director in educational contexts plays a pivotal role in the development and adoption of interventions (Roberts et al., 2015), the preschool director, together with the teachers taking part in the professional development, will be in charge of leading the rest of the staff through the process (Boe and Hognestad, 2017). The researchers will support the implementation process through email, telephone, and visits to each preschool during the intervention period. In addition, a customized website with teaching resources will be provided.

Protocol and Randomization

ACTNOW will have two waves involving different cohorts, the first running from August 2019 to June 2021, and the second from August 2020 to June 2022 (**Figure 3**). The professional development provided in Wave 2 will be adjusted based on experiences and findings from Wave 1. Data collection will have three main stages; pre-testing performed before randomization, 7-month follow-up performed at the end of the professional development, and 18-month follow-up performed 1 year after staff have completed the professional development. In addition, process evaluation measures will be taken throughout the study.

We will cluster randomize at the preschool level, since we regard delivery of the intervention on the preschool level the only practical approach. A third party (Morten Wang Fagerland, Norwegian School of Sport Sciences) will randomize

TABLE 2 | Overview of the professional development (preschool level).

Structure	The professional development will be structured as a 15-credit continuing education module at a master's degree level delivered over 7 months. However, the staff can choose whether they will complete the exam and achieve credits or complete the professional development without credits. Seminars and webinars total 6 days face-to-face (3 days on campus and 3 days locally in each preschool) and multiple webinars, amounting to approximately 50 h in total.
Requirements for participation	We will request the preschool director and minimum one teacher from each classroom to participate. Skilled workers/assistants and others will primarily be involved locally through the processes initiated and facilitated by the director and teacher(s). Yet, preschools can choose to let skilled workers/assistants participate in the professional development, depending on their needs and resources.
Aims/content	The aims of the professional development are to increase the preschool directors' and teachers' competences regarding 1. the importance of physically active play and its relevance for child development, and how to integrate more physically active play (the core components) into the preschool's practice; and 2. planning and implementation of interventions/changing practice, and thus facilitate the ACTNOW implementation process within the entire preschool and its staff.
Process	The professional development has three phases **Phase 1: Setting the stage (2 months)** The professional development will start by an intensive 2-day face-to-face seminar. One part of the seminar will focus on the intervention at the child level, with both practical and theoretical sessions regarding the four core components, as well as general topics on PA and physically active play, motor competence, cognitive development, and didactics. The other part of the seminar will focus on the process of the development work among the preschool staff. The seminar will be followed by a 1-day visit to each preschool by a member of the research group. This visit will include a half-day observation of practice and a 2 h staff meeting, planned by the preschools, including discussion of each preschool's specific PA practice, contextual factors, needs, resources, etc. During this first phase, the directors/teachers will be responsible for drafting a model on how to integrate the four core components into their daily practice, which will be subject to feedback and discussion in an individual webinar with the research group. **Phase 2: Customize the intervention for sustainability (3 months)** The second phase of the professional development will focus on the implementation of each preschool's intervention model at the child level. Based on the initial experiences and discussions in Phase 1, each preschool model will be revised, if necessary, and further developed to meet with the preschool practice and the prescribed intervention dose. During this second phase, multiple webinars will be given to extend the lectures and discussions in Phase 1. A group discussion will be arranged, where participants and the research group meet to share the preschools' experiences regarding the implementation process. **Phase 3: Reflect on and evaluate the intervention (2 months)** The third phase of the professional development will focus on reflection and evaluation of the changed preschool practice regarding the implementation of the preschool's intervention model. Multiple webinars will be given, in addition to a 1-day visit in each preschool, with a new half-day observation, followed by a joint reflection in the whole staff group about the developmental work and (hopefully) changed practices. The professional development will end with a final full-day session of experience sharing among all intervention preschools, focusing on lessons learned and the way forward.

$\approx$ 60 preschools to the intervention group ($\approx$ 30 preschools) or the standard of care control group ($\approx$ 30 preschools). Randomization will be done separately in the two study waves after completing recruitment and before initiating baseline data collection using a random number generator (Stata/SE 15.1, StataCorp LLC, College Station, TX, United States). We will use block randomization (randomly chosen block sizes of 4 and 6) and a 1:1 ratio for the two intervention arms. Blinding of participants and preschools is not possible due to the nature of the experiment. To limit potential biases, the fewest possible assessors involved in project management, data collection, and statistical analysis will have knowledge about the group assignment and the study hypotheses.

Participants

We will invite all preschools (both public and private) in multiple regions in the county of Sogn og Fjordane, Norway, having $\geq$ six 3- to 4-year-old children (i.e., requiring a minimum number of children available for 2-year follow-up) to participate in the study. We will invite all 3- to 5-years-old children enrolled in these preschools (Wave 1: children born 2014–2016; Wave 2: children born 2015–2017). Children who are unable to take part in normal everyday PA as promoted by the preschools as part of the intervention will be excluded from the analyses.

Sample-size calculations are derived from standardized ESs in meta-analyses of interventions investigating preschoolers' objectively measured PAs (Finch et al., 2016) and motor competences (Wick et al., 2017), and schoolchildren's cognition (Alvarez-Bueno et al., 2017b) and learning (Alvarez-Bueno et al., 2017a). Preschool interventions have shown small ESs for long-term interventions delivered by preschool staff targeting PA [ES = 0.07 (three studies, > 6 months) and 0.27 (10 studies, delivered by teachers)] (Finch et al., 2016) and motor competence [ES = 0.32 (six studies, vs 6 months) and 0.41 (eight studies, delivered by teachers)] (Wick et al., 2017). Rather similar ESs are shown for cognition (0.11-0.30) (Alvarez-Bueno et al., 2017b) and learning outcomes (0.16-0.26) (Alvarez-Bueno et al., 2017a) in older children (4-18 years). Derived from a conservative sample-size calculation using standard formulas, including correction for the cluster RCT design, we aim to recruit a minimum of 60 preschools and 800 3- to 4-year-old children to the study. This sample size will allow for uncovering statistically significant standardized ESs (Cohen's d) of 0.25-0.30

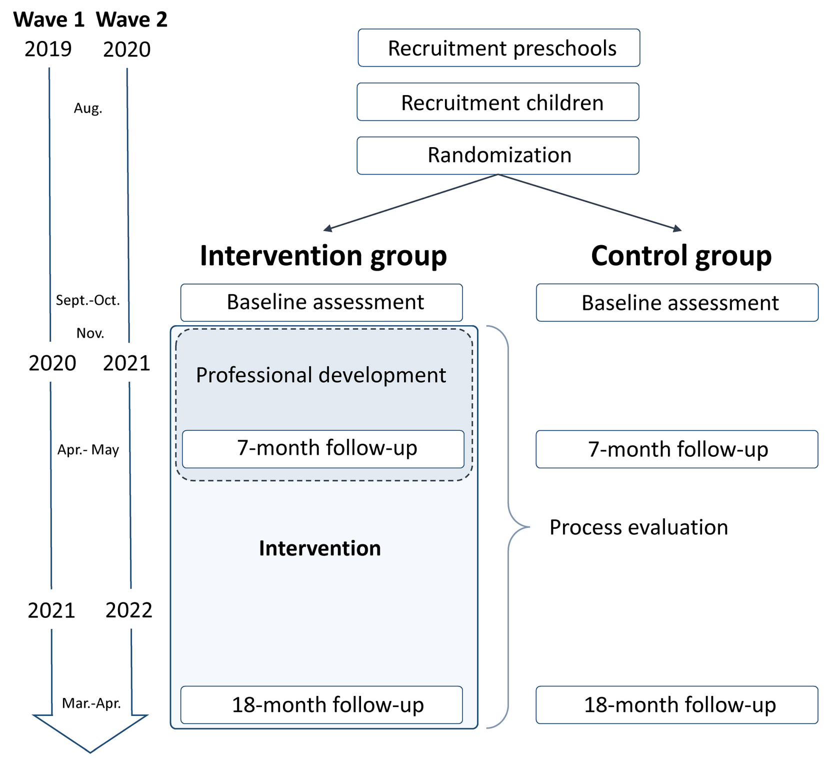

FIGURE 3 | Flow chart of the study.

at the 18-month follow-up, given $A = 0.05$, $1\text{-}\beta = 80\%$, group ratio 1:1, correlation of repeated measurements = 0.6-0.7, intra-class correlation (ICC) across clusters = 0.05-0.10, children per cluster = 13 accounting for 30% attrition among children (median number of 3- to 4-years-old in preschools in Sogn og Fjordane ≈ 18), and coefficient of variation for cluster sample size = 0.65 (Eldridge et al., 2006). Thus, we will require ≈ 400 children and 30 preschools for analysis in each group (intervention; control), given a design effect correction factor = 1.85-2.69. The ICC is estimated using a mean ICC = 0.05 for trials investigating objectively measured PA levels in preschoolers (Finch et al., 2016), results from the Sogn og Fjordane Preschool Physical Activity Study: ICC ≤ 0.10 for PA (Nilsen et al., 2019b) and ICC ≤ 0.05 for motor competence (unpublished), and ICC = 0.07-0.09 for academic performance in schoolchildren (Resaland et al., 2016). Because the sample-size calculation is performed for the 18-month follow-up of 3- to 4-years-old, we will have increased power at the 7-month follow-up, as we also include 5-years-old (minimum total $n \approx 1{,}200$ children); ESs as low as 0.20 can be detected at the 7-month follow-up under the assumptions specified above.

Data and Measurements

The Child Level

Physical activity

We will assess PA objectively over 7 consecutive days using the ActiGraph GT3X + accelerometer (John and Freedson, 2012), which is the most used and validated accelerometer in the field (De Vries et al., 2009; O'Brien et al., 2018). Children will be instructed to wear the accelerometer on the right hip 24 h per day, except during water activities (swimming, showering). Units will be initialized at a sampling rate of 30 Hz, and files will be analyzed at 1-s epochs using the KineSoft analytical software version 3.3.80 (KineSoft, Loughborough, United Kingdom) to correctly capture the lower and higher intensity levels (Aadland et al., 2018a, 2019). In all analyses, consecutive periods of ≥ 20 min of zero counts will be defined as non-wear time (Esliger et al., 2005; Cain et al., 2013). Results will be reported for the overall PA level [counts per minute (cpm)], as well as minutes per day spent sedentary (<100 cpm), in light PA (100–2295 cpm), in moderate PA (2296–4011 cpm), in vigorous PA (≥4012 cpm), and in MVPA (≥ 2296 cpm), determined using the previously established and validated Evenson et al. cut points (Evenson et al., 2008; Trost et al., 2011). As appropriate, sensitivity analyses will be conducted using the Pate et al. cut points (Pate et al., 2006).

In addition to the "standard" PA intensity profile, we will create a dataset having a higher resolution using 33 PA variables of total time (min/day) to capture movement in narrow intensity intervals throughout the spectrum; 0–99, 100–249, 250–499, 500–999, 1,000–1,499, . . ., 14,500–14,999, and ≥ 15,000 cpm. As shown previously (Aadland et al., 2018b; Nilsen et al., 2019a), this dataset will be used to investigate the PA signature associated with relevant outcomes.

PA during the whole day, week, and weekend days, as well as PA during care hours (08:30–15:30) and afternoon hours

(15:30–23:59) on weekdays only, will be analyzed to specifically assess intervention effects during care hours and to assess possible compensatory behavior outside the preschool domain (Gomersall et al., 2013; Nilsen et al., 2019b). Data for a full day will be analyzed with wear-time requirements of $\geq$ 8 h/day and $\geq$ 3 weekdays + $\geq$ 1 weekend day, whereas $\geq$ 5 and $\geq$ 3 h/day of monitoring for $\geq$ 3 weekdays will be used as wear requirements for care hours and afternoons, respectively.

Screen time will be assessed using a parent questionnaire adapted from the Sunrise study protocol (Sunrise, 2020). Measurement properties of the questionnaire will be documented.

Physical fitness and motor skills

The fitness assessment in the ACTNOW study is based on three items (handgrip strength, standing long jump, and speed-agility) from the Assessing FITness in PREschoolers (PREFIT) battery (Ortega et al., 2015). PREFIT is an adaptation of the ALPHA-Fitness: field-based fitness tests for the assessment of health-related physical fitness in children and adolescents, and have demonstrated good reliability in young children (Castro-Pinero et al., 2010; Artero et al., 2011; Ruiz et al., 2011). Hand-grip strength will be measured with a hand dynamometer with adjustable grip (TKK 5001 Grip A, analog model (Cadenas-Sanchez et al., 2016), measurement range 0–100; Takey, Tokio Japan), and a grip—span of 4.0 cm (Sanchez-Delgado et al., 2015). Lower body explosive strength will be measured using standing long jump, where children are instructed to jump as far as possible, measured in centimeters. Speed-agility will be assessed using a shuttle running test where children are instructed to run 4×10 m as fast as possible, measured in seconds.

To evaluate fundamental motor skills (FMS), we developed a test battery guided by the "Test of Gross Motor Development 3" (TGMD-3) (Ulrich, 2013, 2019). TGMD-3 is designed for children aged 3–10 years, and originally based on observation of children's movements across 13 tasks within the two domains: locomotion (run, skip, slide, gallop, hop, and horizontal jump) and ball/object control (hereafter referred to as "object control") (overhand throw, underhand throw, catch, dribble, kick, one-hand strike, and two-hand strike). We modified this test battery to reduce the participant and researcher burden, and at the same time cover the three main domains of FMS by including balance skills (Sun et al., 2010). We therefore included six movement items from the TGMD-3 battery (run, horizontal jump, hop, catch, overhand throw, and kick), in addition to three movement items within the balance domain (single leg standing, walking line forward, and walking line backward) from the Preschooler Gross Motor Quality Scale (PGMQ) proposed by Sun et al. (2010). The specific items were selected based on their relevance (e.g., some of the movement items in the TGMD-3, like the baseball strike and dribble, are less common and therefore less relevant in assessments of Norwegian children), and variety (e.g., including object control skills related to both hands and feet, and adding both static and dynamic balance tests) to broadly capture children's skills within the three FMS domains. We have previously demonstrated good inter-rater reliability for this FMS battery (Nilsen et al., 2019a).

Children's fitness and FMS will be evaluated in small groups (4–5 children) during preschool hours, in a safe environment with enough space to move freely. Each child performed each task twice, and skills will be completed in a standardized order, using approximately 40 min per group. The test teams consist of one instructor who provide a verbal description and demonstration of the required skill, while a separate assessor observe and score the performance. The physical fitness and FMS tests are administered and scored according to the TGMD-3 (locomotor and object control skills), PGMQ (balance skills), and PREFIT-protocols (hand grip strength, standing long jump, speed-agility). Briefly, each of the nine FMS movement tasks is described by three to four performance criteria, which is scored 0 or 1 if a criterion is absent or present, respectively. Scores are summed for each task and each domain.

Anthropometry and demography

We will assess children's body mass, height, and waist circumference according to the PREFIT battery (Ortega et al., 2015). Body weight will be measured to the nearest 0.1 kg using an electronic scale (Seca 899, SECA GmbH, Hamburg, Germany), and height will be measured to the nearest 0.1 cm with a portable stadiometer (Seca 217, SECA GmbH, Hamburg, Germany). Body mass index (kg/m^2) is calculated and children classified as normal weight, overweight, or obese based on criteria proposed by Cole et al. (2000). Waist circumference will be measured twice to the nearest 0.1 cm at the level of the umbilical zone. Demography includes the variables socioeconomic status (parents' education and income), children's and parents' origins, children's birth weights, parents' weight status, and parents' PAs, and they will be measured by parent questionnaires.

Sleep

Children's sleep will be assessed using 24 h accelerometry and a parent questionnaire. Accelerometry has been applied to assess sleep in multiple studies in preschoolers and older children (Galland et al., 2018), although procedures for assessment of sleep are less developed than for movement behaviors (Migueles et al., 2017). Most of these studies have applied wrist-worn accelerometers (Migueles et al., 2017; Galland et al., 2018), but there are ongoing efforts to assess and develop measurement properties of sleep for waist-worn accelerometry (Hjorth et al., 2012; Zinkhan et al., 2014; Barreira et al., 2015). There is currently no validated accelerometry-based sleep scoring algorithm for preschoolers (Migueles et al., 2017). We will therefore use the scoring algorithm by Sadeh et al. (1994), which is developed for assessment of sleep in children and youth, and incorporated by ActiGraph (ActiLife), as the starting point. However, since this algorithm was developed for wrist-worn accelerometers, using it with waist-worn accelerometers should be done with care since results are not directly comparable (Hjorth et al., 2012; Zinkhan et al., 2014). Alternative scoring protocols developed with or validated for waist-worn accelerometers, for example as suggested by Barreira et al. (2015), will therefore be used as appropriate, if improved measurement properties can be demonstrated in preschoolers.

In the questionnaire, adapted from the Sunrise study protocol (Sunrise, 2020), parents are asked to report children's sleep duration (including nap time), when they go to bed, when they wake up, and whether these patterns are consistent. Furthermore, they will rate children's sleep quality (1–7 scale). Measurement properties of the questionnaire will be documented.

Socioemotional health, self-regulation, executive function, and learning

We will adapt several validated tests to examine different aspects of socioemotional health, self-regulation, executive functions, and learning. Yet, there exists little agreement on the optimal measures and their configuration for capturing important aspects of early cognitive development (Garon et al., 2008; Howard and Melhuish, 2017).

To assess **socioemotional health,** we will ask the teachers to fill out the Strengths and Difficulties Questionnaire (SDQ) for each child. The SDQ is a brief measure of psychosocial strengths and problems in 3- to 16-years-old children. The SDQ asks about 25 attributes (10 positive, 14 negative, and 1 neutral) divided between five subscales of five items each: (*1) Emotional Symptoms Scale; (2) Conduct Problems Scale; (3) Hyperactivity Scale; (4) Peer Problems Scale;* and (*5) Prosocial Scale*. All but the last scale are also summed to give a total difficulties score. SDQ uses a 3-point Likert scale to indicate the extent to which each attribute applies to a child ("not true," "somewhat true," or "certainly true") (Goodman, 1997, 2001). The construct validity of the SDQ has been demonstrated in several studies (Goodman, 2001; Stone et al., 2010; Mieloo et al., 2012), and the reliability and validity of the SDQ has been shown to be satisfactory (Goodman, 2001; Stone et al., 2010). The teacher version of the SDQ has shown both higher internal consistency and test-retest reliability compared to the parent version for preschool and schoolchildren (Stone et al., 2010; Mieloo et al., 2012).

Self-regulation will be assessed both by teacher-report and a structured observation (direct measure) of a child's performance. Teachers will be asked to fill out the 33-item Child Self-regulation and Behavior Questionnaire form from the Early Years Toolbox (EYT) (Howard and Melhuish, 2017). The Child Self-regulation and Behavior Questionnaire generates subscales on cognitive, behavioral, and emotional self-regulation, in addition to sociability, prosocial behavior, externalizing and internalizing problems, which overlaps with the SDQ. Each item asks the teacher to evaluate the frequency of target behaviors of each child on a scale from 1 (not true) to 5 (certainly true). The subscales of the questionnaire have been shown to be reliable in preschoolers (Howard and Melhuish, 2017).

The directly assessed Head-Toes-Knees-Shoulders task assesses the ability of a child to use and integrate the executive functions to control and direct actions, pay attention, and remember instructions (Cameron Ponitz et al., 2008; Ponitz et al., 2009; Cameron et al., 2012; von Suchodoletz et al., 2013). To respond correctly, the task requires that children listen to instructions, remember and execute gross motor movements in relation to directions, and inhibit pre-potent incorrect responses. In the first part (10 items), two rules are paired: "touch your head" with "touch your toes." In the second part (10 items), two more paired rules are added: "touch your knees" with "touch your shoulders" (Ponitz et al., 2009). Children are instructed to perform the opposite of the dominant response. Hence, the command to "touch your head" requires the children to touch their toes, and the command to "touch your shoulders" requires the children to touch their knees. If the children reach a minimum performance threshold of 4 points on both of these levels (2 points are given for a correct response, and 1 point for a self-corrected response), a third section (10 items) will be given, where the paired rules are switched (i.e., head goes with knees and shoulders go with toes) (McClelland et al., 2014). Instructions will be given verbally in a fixed order, without feedback. Preceding each level, four practice trials and up to three attempts on each are provided to familiarize with the test (Cameron Ponitz et al., 2008). The Head-Toes-Knees-Shoulders task is quick to administer, requires few materials, and has shown construct validity in European samples (von Suchodoletz et al., 2013).

We will assess all three key **executive functions** identified by Miyake et al. (2000): inhibition, working memory, and cognitive flexibility. These three executive functions will be measured using assessments from the iPad-based EYT (Howard and Melhuish, 2017). EYT has shown good reliability, convergent validity with existing measures, and developmental sensitivity (Howard and Melhuish, 2017). The EYT is developed for preschool children (which contrasts the majority of measures that are modified adult versions), with emphasis on being (a) developmentally appropriate, (b) developmentally sensitive, (c) brief, (d) engaging, (e) technologically dynamic without introducing effects of technological expertise, and (f) internationally applicable. The EYT is available on iTunes App Store. We embedded a Norwegian version to ensure its application in the children's native language.

To measure the visual-spatial working memory we will use *"The Mr. Ant task"* (Howard and Melhuish, 2017). In this task, children are asked to remember spatial locations of "sticker/s" that are placed on Mr. Ant's body. The children then, after a brief retention interval, tap the spatial locations where they believe the stickers were on Mr. Ant. The test trials increase in difficulty by increasing the number of stickers on Mr. Ant's body (progressing from one to eight stickers). All trials progress as follows: (a) Mr. Ant presents with n colored stickers for 5 s, (b) the screen is blank for 4 s, and then (c) an image of Mr. Ant without stickers – along with an auditory prompt to recall where the stickers were – is presented until the child's response is complete. The task continues until completion, or until failure on all three trials at the same level of difficulty. Children are given instruction and three practice trials to familiarize them with task requirements prior to administration of test trials. Working memory will be indexed by a point score calculated as follows: starting from Level 1, 1 point for each passed level (at least two of the three trials performed accurately), plus 1/3 of a point for all correct trials thereafter (Howard and Melhuish, 2017).

To measure inhibition, we will use *"The Go/No-Go task"* (Howard and Melhuish, 2017). In this task, the children are asked to catch the fish (Go trial) by tapping the screen when they see a fish, and to avoid the shark (No-Go trial) by not tapping the screen when they see a shark. Because the majority of the stimuli are Go trials (80% fish), this generates a pre-potent response to tap the screen, requiring the children to inhibit this response (not tap) in No-Go trials (20% sharks). The children are given instructions and practice to familiarize with requirements as follows: go instructions, followed by five practice Go-trials; No-Go instructions followed by five practice No-Go trials; combined Go/No-Go instructions followed by a mixed block of 10 practice trials (80% Go-trials); and a recap of instructions. Feedback in the form of auditory tones is provided on all practice trials. The task proceeds with 75 stimuli divided evenly in three 1-min test blocks (each separated by a short break and a reiteration of instructions). Blocks always begin with a Go stimulus, and no more than two successive trials are No-Go stimuli. Each trial involves a presentation of an animated stimulus (i.e., fish or shark) for 1,500 ms, separated by a 1,000 ms interstimulus interval. The outcome is an impulse control score that is the product of proportional Go and No-Go accuracy (Howard and Melhuish, 2017).

Cognitive flexibility/shifting will be measured by the "*The Card Sorting task.*" This task asks the children to sort red rabbits and blue boats by either color or shape, into two locations (identified by a blue rabbit and a red boat). As the card sorting rules alternate, the children must switch between rules. The children are first given a demonstration trial and two practice trials. Then they are asked to sort stimuli by one dimension for six trials (with the same stimulus never presented more than twice in a row). In the subsequent post-switch phase, children are required to sort by the other sorting dimension, as prompted by auditory instructions preceding post-switch test trials. If the child correctly sorts at least five of the six pre- and post-switch stimuli, they proceed to a border phase of the task. In this phase, children are required to sort by color if the card has a black border or sort by shape if the card has no black border, preceded by a demonstration trial and two practice trials. This sorting rule is reiterated prior to all test trials. Scoring represents the number of correct sorts after the pre-switch phase (Howard and Melhuish, 2017).

As a proxy for **learning** we will use "*The Expressive Vocabulary*" for language development (Howard and Melhuish, 2017) and "*The Numbers task*" for early math skills (manuscript not published), both from the EYT. Both measures have shown good convergent validity and reliability (Howard and Melhuish, 2017). In the Expressive Vocabulary task, consisting of 54 items, children are asked to verbally produce a correct label for the depicted nouns and verbs. The administrator records the response directly into the iPad app (correct/not correct). In cases of an incorrect label, the administrator will prompt the children by asking, "What else might this be called?" until either a correct production or an indication that the child is unable to produce the target word. A six-item failure stop rule will be used to minimize administration time. Expressive Vocabulary performance will be scored as overall accuracy (Howard and Melhuish, 2017).

The Numbers task consists of 79 items pertaining to numerical concepts (e.g., many), spatial and measurement concepts (e.g., tallest), counting subset (e.g., counting dogs interspersed with cats), matching digits and quantities (e.g., understanding the correspondence between: spoken number *two*, the digit *2*, and its corresponding quantity), number order (e.g., identifying the missing number in a number line), ordinality (e.g., identifying higher/lower numbers), cardinality (e.g., identifying what is 1st, 2nd, etc.), subitizing (e.g., a rapid appraisal of quantities as having more or less), patterning (e.g., identifying and completing a pattern), and numerical word problems and equations. In this task, children respond to each item either by tapping the iPad screen or verbally answer auditory questions in the app (which is recorded directly in the app by the administrator). The app integrates automated start rules based on the age of the child, and stop rules after five consecutive incorrect responses.

The Preschool Level

The aim of the process evaluation is to explore how staff in the intervention preschools respond to their enrollment in professional development and how the proposed new way of working with PA gains traction in different contexts. We aim to explore the processes and mechanisms through which professional development, alongside working in partnership with researchers, influence the way staff organize and integrate PA practices into their daily operations. We will also explore *if* and *why* intervention effects may vary between preschools. The flexible intervention approach, and thus the variation in activities (likely) taking place in each preschool, means that an examination of typically quantitative measures of implementation such as fidelity, dosage, and adherence might be less feasible and informative. Hence, the process evaluation includes complementary qualitative and quantitative measures of implementation to support the evaluation of the intervention's ability to change practice, as also recommended previously (Bonell et al., 2012; Pesce et al., 2016).

Staff experiences and perspectives

To provide in-depth accounts of how the intervention preschools develop and implement PA into their daily operations, all intervention preschools will be invited to participate in a qualitative study. Data will be collected using semi-structured in-depth interviews and focus groups. More specifically, in-depth interviews will be used to explore the views of the teachers enrolled in the professional development regarding the relevance and delivery of it. For example, teachers will be asked about how they make sense and engage with the central components of the ACTNOW professional development program. Further, in-depth interviews will be used to explore the directors' and teachers' roles in leading the development work taking place in each preschool. For example, questions will be asked to explore how they perceive their role in driving the intervention and the preschool's PA practices forward as well as what actions and procedures they plan to undertake to lead the process. Focus groups will be used to explore how *all* staff perceive the role of environmental mechanisms in shaping the integration of PA practices into their daily operations. More specifically, staff will be asked about their collective understanding of the intervention and its core components.

They will also be asked about their willingness to engage in the developmental work taking place in each preschool and what mechanisms that either promote or hinder engagement and participation.

The literature on implementation, in particular the Normalization Process Theory (May and Finch, 2009), and the characteristics of the ACTNOW project and logic model, have been used to inform the interview guides. The interview guides will be revised and adjusted during data collection to allow for the inclusion of case-specific questions and more detailed exploration of emerging themes. As recommended by Durlak (2016), data will be collected at several time points to allow for an examination of the process of implementation over time. Therefore, the intervention preschools will be approached twice while staff participate in the professional development during Year 1 (once at the beginning and once at the end of the period) and once after its completion during Year 2.

Informed by the findings from the qualitative study conducted during the first wave, we will also develop a survey that will be administered during Wave 2 to all members of staff in the intervention preschools. The aim of this survey is to develop theories about how the identified mechanisms in the qualitative findings play out in contexts with different preschools, staff, and children.

Evaluation of written plans

As part of the professional development, we will work with and strongly advise all preschools to anchor the child-level core components of the intervention in their written policies and plans. This work will extend the assessment of existing policies and practices as well as the customized intervention aims and models developed in Phase 1 of the education module. We will use these plans to assess to what extent the intervention is integrated in the preschools' policies and daily operation over the short- and long-term.

Participation and engagement in professional development

Participation in the professional development courses and lectures, as well as completion of tasks related to the implementation process, for example, making aims, drafting models of how the preschool will work to incorporate the intervention, and experience sharing, will be logged to allow for a thorough evaluation of the intervention implementation.

Observation of the movement environment

The preschools' movement environment quality and educational practice will be assessed using the Movement Environment Rating Scale (MOVERS) (Archer and Siraj, 2017) observational scale. This scale captures the quality of the early learning environment and practice based on the presence or absence of high-quality experiences and practices identified as being influential for children's later outcomes. The scale is completed by highly trained and reliable raters through a fly-on-the-wall observation of a preschool room, conducted across a full day and is supplemented by a review of documentation and discussion with an educational leader. All rooms will be scored at baseline, whereas the scale will be used to support and evaluate the implementation process in the intervention group at later time points.

The MOVERS consists of four subscales relating to quality of experiences and practices related to children's physical development, namely: (*1) curriculum, environment and resources for physical development* (4 items); (*2) pedagogy for physical development* (3 items); (*3) supporting physical activity and critical thinking* (3 items); and (*4) parents/carers and staff* (1 item). The score ranges from 1 to 7, where 1 = inadequate, 3 = minimal, 5 = good, and 7 = excellent. These quality rating scores are determined by in-balance judgments of the pattern of presence or absence of quality indicators for each item. The MOVERS has been used and validated outside Norway, and we will consider whether it needs adapting to the Norwegian context during the project period.

Staff Physical activity

Staff PA will be assessed using accelerometry, which will be performed simultaneously with the three child measurements. We will use the same procedures as detailed for children above, except using another criterion for non-wear time and other cut points to determine intensity-specific PA. Consecutive periods of $\geq$ 60 min of zero counts, allowing for 1–2 min of non-zero counts, will be defined as non-wear time, according to previous studies in adults (Troiano et al., 2008; Hansen et al., 2012). Results will be reported for overall PA level (cpm), as well as minutes per day spent sedentary (<100 cpm), in light PA (100–2,019 cpm), in moderate PA (2,020–5,998 cpm), in vigorous PA ($\geq$ 5,999 cpm), and in MVPA ($\geq$ 2,020 cpm), determined using the previously established Troiano cut points (Metzger et al., 2008). Consistent with children's activity patterns and handling of child data, results will primarily be analyzed using short epochs (1 s) to allow for capturing short intermittent bursts of PA. Sensitivity analyses using 60-s epochs will be performed as needed for comparison with previous adults studies (Troiano et al., 2008; Hansen et al., 2012).

Data Management

High-quality data collection, data management, and data analysis is of crucial importance to ensure valid study results and secure privacy protection of participants. Prior to the data collection, all assessors will perform thorough training in how to instruct and score children on the different measures to ensure high interrater reliability and minimal measurement error.

Non-digital data on main child-level outcomes (anthropometry, physical fitness, motor competence, and self-regulation) will be double-checked for 100% of cases and triple-checked for a random sample of 10% of cases. Other sources of non-digital data will be double-checked using a random sample of 25% of preschools. After the thorough quality control of data, the database will be locked prior to opening the group allocation (1- and 2-years follow-up) and prior to performing any statistical analysis.

Data handling and storage are confidential and will be managed according to the Western Norway University of Applied Sciences internal control system in accordance with Norwegian privacy protection regulations/the General Data Protection Regulation (EU 2016/679).

Analysis Plan

The Child Level

Primary aim

The main analyses of child-level effects will employ an intention-to-treat principle, thus including all subjects and preschools originally allocated to the respective groups, to test the study's effectiveness (Polit and Gillespie, 2010). However, as shown for the school setting (Donnelly et al., 2009), there are strong arguments for including per-protocol analyses for the examination of efficacy. Therefore, we will perform secondary analyses limited to preschools that exhibit acceptable intervention adherence. Missing data will be sought, minimized, detailed, and handled in line with suggested guidelines (Little et al., 2012). Attrition analyses will be performed to investigate whether missing data are related to child characteristics. Missing data will be handled by the use of linear mixed models (LMMs) and structural equation modeling (SEM) (Enders, 2011; Little, 2013).

Intervention effects will be evaluated by testing for time*group interactions for all outcomes. The per-protocol analysis will be adjusted for differences between the groups, as appropriate. LMM and multilevel SEM for mediation analyses (SEM) (Little, 2013) will be used to account for clustering of observations on the preschool level in all analyses. A two-sided $p \leq 0.05$ is considered statistically significant; however, both ESs and patterns of effects across variables will be considered of greater importance than *p*-values when drawing study conclusions. Consistent with this approach, *p*-values will not be adjusted for multiple testing. Main analyses will be performed using IBM SPSS v. 25 (IBM SPSS Statistics for Windows, Armonk, NY: IBM Corp., United States) or later versions and MPLUS v. 8 or later versions (Muthén and Muthén, Los Angeles, United States). Reporting will be done in accordance with the CONSORT statement (Campbell et al., 2012).

We regard children's cognition as the main study outcome. However, we include several aspects of cognition in the present study (socioemotional health, self-regulation, executive functions, and learning), of which designating one focused outcome *a priori* is challenging and inappropriate based on the current level of evidence of effects of PA in young children (Carson et al., 2016; Alvarez-Bueno et al., 2017a,b; Singh et al., 2019). These constructs will be analyzed as separate variables, to retain their unique information, as well as latent variables, to remove measurement error and establish broader constructs, and thus obtain both specific as well as broader knowledge about the effect of PA on cognitive outcomes. Children's PA, physical fitness, motor competence, adiposity, and staff PA are regarded secondary outcomes.

Secondary aim

Secondary analyses of intervention effects. A priori-defined moderation and mediation analyses will be performed to study child characteristics and pathways that may be important for the effect of the intervention. For example, evidence shows that PA interventions in school are most beneficial for those most in need (Resaland et al., 2016, 2018a) and possibly more beneficial for boys than for girls (Resaland et al., 2018b). Thus, we will test for effect moderation by sex, age, socioeconomic status, and baseline levels of outcomes. We will test for mediation of effects through hypothesized pathways including self-regulation/executive functions as mediators between PA and learning (Howie and Pate, 2012), and socioemotional characteristics, physical fitness, motor skills, and adiposity as mediators between PA and cognitive outcomes (Tomporowski et al., 2011). Mediation analyses include the use of SEM. Importantly, because we include three time points, the design allows for testing a full mediation model (Little, 2013).

Association analyses. The large sample allows for analyses of distributions and correlates among the included variables in cross-sectional analyses, as well as analyses of development and tracking over time, and analyses of determinants of change in outcomes in longitudinal analyses in the control group. Cross-lagged panel analysis will be used to determine reciprocal relationships among variables over time (Little, 2013). If there are small and non-significant intervention effects, longitudinal analyses will include both groups to increase power of these analyses. In addition to standard regression models, we will use multivariate pattern analysis (Aadland et al., 2018a,b) to explore multivariate association patterns among the included variables. These analyses include associations related to intervention effects performed by associating changes over time (exposure) to group (outcome), to support the interpretation of the study effects. Multivariate pattern analysis will be performed in Sirius v.11 (Pattern Recognition Systems AS, Bergen, Norway); otherwise, we will use the same statistical models (LMM and SEM) and software, as specified above.

The Preschool Level

The individual interviews and focus groups will be recorded, transcribed verbatim, and imported with field notes of observations and documents from each preschool into NVivo-11 for data management. The data will be thematically analyzed following the procedures proposed by Braun and Clarke (2006). The Normalization Process Theory will provide a conceptual framework to understand and evaluate how staff make sense of the intervention (coherence), engage with the professional development (cognitive participation), integrate PA practices in their preschool's daily practices (collective action), and evaluate the effects of improved quality and quantity of PA practices into their daily operations (reflexive monitoring). Data will be analyzed subsequently and arranged into, within, and between preschool data displays to explore convergences and divergences between the case study preschools. The preliminary displays will also help to identify potential themes and gaps in the data that need to be explored during the second and third round of data collection.

Staff PA will be analyzed using similar statistical approaches as described for child-level outcomes above (i.e., effects will be determined using a between-group comparison). For other data, analyses will be restricted to examination of main effects of time because we only include repeated measurements for the intervention group. Preschool level data will be used as a basis for per-protocol efficacy analyses of individual level outcomes. For these analyses, preschool level data will be used to decide which preschools should be included using appropriate cut points for acceptable participation and engagement in the intervention activities and/or by including these data as explanatory variables in regression models. In association analyses between individual and preschool level data, data will be combined using preschool averages.

DISCUSSION

We believe professional development of staff and a whole-child approach that integrates physical activity with challenging motor tasks, cognitively engaging play, and learning activities in the early childhood education and care setting, may provide a feasible venue to favorably affect different aspects of both physical and cognitive development in young children. Thus, the ACTNOW intervention model might provide an efficient, acceptable, and sustainable way to build human capital (Bailey et al., 2013) and provide an early solution to lifelong public health and developmental challenges. Of importance for the dissemination and scaling, our intervention model is framed within an education module that may be included in early childhood education and care educational programs. We regard this feature a significant strength of our approach. In addition to this feature, we regard the co-creation of the intervention in partnership with staff, a vital premise for creating sustainable effects that have the potential to extend beyond previous effectiveness studies (Finch et al., 2016; Wick et al., 2017). In this way, we lay the foundation for the intervention's unique operationalization within each preschool's context, which value and foster the preschool staff's autonomy and ownership.

While the flexible and holistic nature of this effectiveness trial has the advantage of testing intervention effects in a real-word setting, the effects of the multifaceted intervention will be compared with those of "business as usual." The absence of another experimental group with different intervention characteristics limits our ability to improve the understanding of which specific features of the intervention are responsible for any observed effects. However, the inclusion of outcome measures supposed to capture child development across all four core components of PA could be partly applied to elucidate such effects. Most importantly, though, the aim of the study is not to provide evidence in support of specific hypothesis of the PA-cognition relation (Best, 2010; Meeusen et al., 2018), but to test a pragmatic program of enriched and meaningful PA that with minimal adjustment could be adopted by preschools and improve children's everyday opportunities to take part in developmentally appropriate physically active play.

While randomized trials are highly valued and regarded as the gold-standard approach for making causal inferences, conducting large-scale cluster RCTs with comprehensive and demanding interventions in educational settings poses substantial challenges. It requires acceptance, motivation, and substantial support from preschool owners, directors, and staff, which builds on mutual respect and trust, and a solution-oriented spirit, between researchers and the practice field. To this end, we have no guarantee that ACTNOW will succeed with regard to its implementation and with regard to producing positive child developmental outcomes. These challenges, though, provide a strong rationale for including a comprehensive process evaluation to capture how, why, and for whom the intervention may or may not work (Bonell et al., 2012). Thus, irrespective of the success of the study, we aim to improve knowledge on contextual mechanisms underpinning how the intervention interacts with and produces various organizational outcomes to increase probability of success of future interventions and scaling.

DISSEMINATION

ACTNOW has the potential to reach a large number of children, parents, teachers, preschools, and authorities, and thereby may serve as a vehicle to positively influence policy in the preschool sector. Beyond sharing knowledge in scientific channels and in popular science, dissemination on local, regional, and national levels will have several components. First, if the professional development/continuing education is successful, we will be able to offer it as part of the university's educational provision in the long-term. Second, we will use established meeting arenas to inform and stimulate an ongoing dialogue with municipalities and other local, regional, and national stakeholders. Collectively, this means that the distance from testing to widespread dissemination is short, which will promote scaling of the intervention in a real-world context.

ETHICS STATEMENT

The study is approved by the Institutional Ethics Committee and the Norwegian Centre for Research Data (reference number 248220). ACTNOW will study children, a vulnerable group that is unable to give valid consent. We will obtain written informed consent from each child's parent/guardian prior to testing. Children will be informed about the study procedures on their premises. We will perform all child testing in close collaboration with preschool staff to provide a safe environment for children. Testing will be terminated if a child expresses discomfort. Similar to children/parents, staff will provide written informed consent, specifically tailored to the research activities they participate in, prior to all testing. Procedures and methods will conform to the ethical guidelines defined by the World Medical Association's Declaration of Helsinki and its subsequent revisions (World Medical Association [WMA], 2017).

AUTHOR CONTRIBUTIONS

EA and KA drafted the study protocol. All authors contributed to the design of the study, provided input on the protocol, and approved the final version for publication.

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REVIEW
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Physical Literacy - A Journey of Individual Enrichment: An Ecological Dynamics Rationale for Enhancing Performance and Physical Activity in All

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Internationally, governments, health and exercise practitioners are struggling with the threat posed by physical inactivity leading to worsening outcomes in health and life expectancy and the associated high economic costs. To meet this challenge it is important to enhance the quality, and quantity, of participation in sports and physical activity throughout the life course to sustain healthy and active lifestyles. This paper supports the need to develop a physically literate population, who meaningfully engage in play and physical activity through the development of functional movement skills in enriched environments. This is a shift away from reductionist approaches to physical activity engagement and maintenance to an ecological dynamics approach that focuses on enrichment to support functional movement skill learning and development. This is an embedded approach to physical literacy that allows learners the space and time to "explore–discover" (ecological psychology) within environments that will lead to a concomitant self-organization of highly intricate network of co-dependent sub-systems (anatomical, respiratory, circulatory, nervous, and perceptual-cognitive) resulting in functional movement solutions for the performance task and enduring positive adaptations to subsystems supporting the physical literacy journey across the life course. "Explore-discover adapt" is at the heart of two contemporary learner-centered pedagogies: Non-linear Pedagogy (NLP) and the Athletic Skills Model (ASM). Both emphasize the importance of enrichment experiences from an early age, and throughout life course, and both appreciate the inherent complexity involved in the learning process and the importance of designing a rich and varied range of athletic, participatory experiences that will support the embedded development of physical literacy leading to ongoing physical activity for all.

The final part of this paper will demonstrate the potential of an ecological dynamics approach for supporting the concept of physical literacy by providing a roadmap for a reliable and valid measurement of physical literacy when considered from both an ecological dynamics perspective and the phenomenology understanding of physical literacy.

Keywords: non-linear pedagogy, athletics skills model, motor learning, ecological psychology, executive function, physical education, sport coaching

INTRODUCTION

Across the globe more than 1.4 billion adults do not meet the recommended levels of physical activity (Guthold et al., 2018). The international pandemic of people leading sedentary lives is responsible for over five million deaths and an economic burden in excess of £50 billion per year (Lee et al., 2012; Ding et al., 2016). According to Ward et al. (2019) by 2030 in the United States of America: (i) one in two adults will be obese; (ii) the prevalence of obesity will be higher than 50% in 29 states and not below 35% in any state; and (iii), nearly one in four adults is projected to have severe obesity. Across the world health and exercise practitioners and academics, such as physical educators and exercise scientists, are challenged to resolve the massive threat posed by physical inactivity levels to the quality of people's lives. Given the impact of this global health pandemic on life expectancies and quality of life, as well as the internationally burgeoning health bill, some have advocated a shift away from individualized approaches to behavior change and small scale individual quick fix interventions, to large scale systems-based interventions that are outward facing, prioritizing the role that the design of environments plays in sustainable physical activity promotion (Leone and Pesce, 2017; Ding et al., 2020). Referring to Baumann's "liquid society," Abu-Omar et al. (2019) have suggested that contemporary physical activity policies have entered a "liquid" age, in which promotion efforts are global and multi-sectoral. They have called for a balance of this all encompassing view with more focused approaches which should have a more limited and identifiable scope and, therefore, potentially greater effectiveness.

In line with suggestions of Davids et al. (2016) it is important to enhance the quality, as well as the quantity, of participation in sports and physical activity throughout the life course. A well-defined and important scope for applied scientists and practitioners, exercise scientists and physical educators is to supporting children and adults of all ages to develop and maintain meaningful engagement in play and physical activity through the development of functional movement skills (**Figure 1**). Being competent in a broad range of movement skills is essential to promote enjoyment of, and engagement in, a range of different sports, physical activity and exercises in order to sustain healthy and active lifestyles across the lifespan (Robinson et al., 2015). Thus, the learning of movement skills which can enhance children's functionality (i.e., capacity to participate meaningfully) in play, games and activities can: (i) contribute to positive trajectories of physical, mental and socio-emotional health throughout childhood (Robinson et al., 2015) and (ii) underpin the acquisition of skills and expertise needed by athletes to perform at a high level in sports (Savelsbergh and Wormhoudt, 2019) (iii) support all individuals at any stage of the life course in participation in sport, physical activity and exercise at a recreational level (Hulteen et al., 2018).

MOVEMENT SKILLS EMBEDDED: AN ECOLOGICAL DYNAMICS RATIONALE TO SUPPORT THE EMERGENCE OF PHYSICAL LITERACY CAPACITIES ACROSS THE LIFE COURSE

Children and adults who have acquired a broad range of movement skills are easily recognizable by the way they read and interact with their environment, for example moving to avoid an object, jumping over a puddle or kerb in the street or intercepting a ball at full stretch in the playground or on the sports field (Whitehead, 2001). The physical literacy journey is an enduring and constant process that begins at the start of life when we are unable to travel from one place to another, or coordinate our limbs to feed ourselves. Over the next decade, given opportunity to meaningfully invest in physical activity, children will develop, expand, and refine their physical, perceptual and cognitive capacities through performing functional movement skills during play making the transition from merely surviving, to thriving through meaningful embodied engagement in their environment and context (Adolph and Hoch, 2019). However, in many countries a high proportion of children do not have sufficient opportunities to engage meaningfully in physical activity and physical activity progressively declines while sedentary behavior increases, typically from the age of school entry (Van Hecke et al., 2016; Colley et al., 2017; Pearson et al., 2017). The on-cost of this problem is that today, children do not have as functional a movement skills repertoire as possessed their parents, or grandparents, and with it other integral aspects of physical literacy fall by the way side (physical, perceptual, and cognitive capacities) which previous generations acquired subconsciously through play. In summary, today's generation of children are unlikely to engage as meaningfully in lifelong physical activity as earlier generations (Barnett et al., 2011; Tester et al., 2014; Bardid et al., 2015). Empirical evidence also suggests that children who do have well-developed functional movement skills seek out physical activity and experience better health outcomes compared to their peers who present low physical activity and high sedentary behavior levels (Robinson et al., 2015).

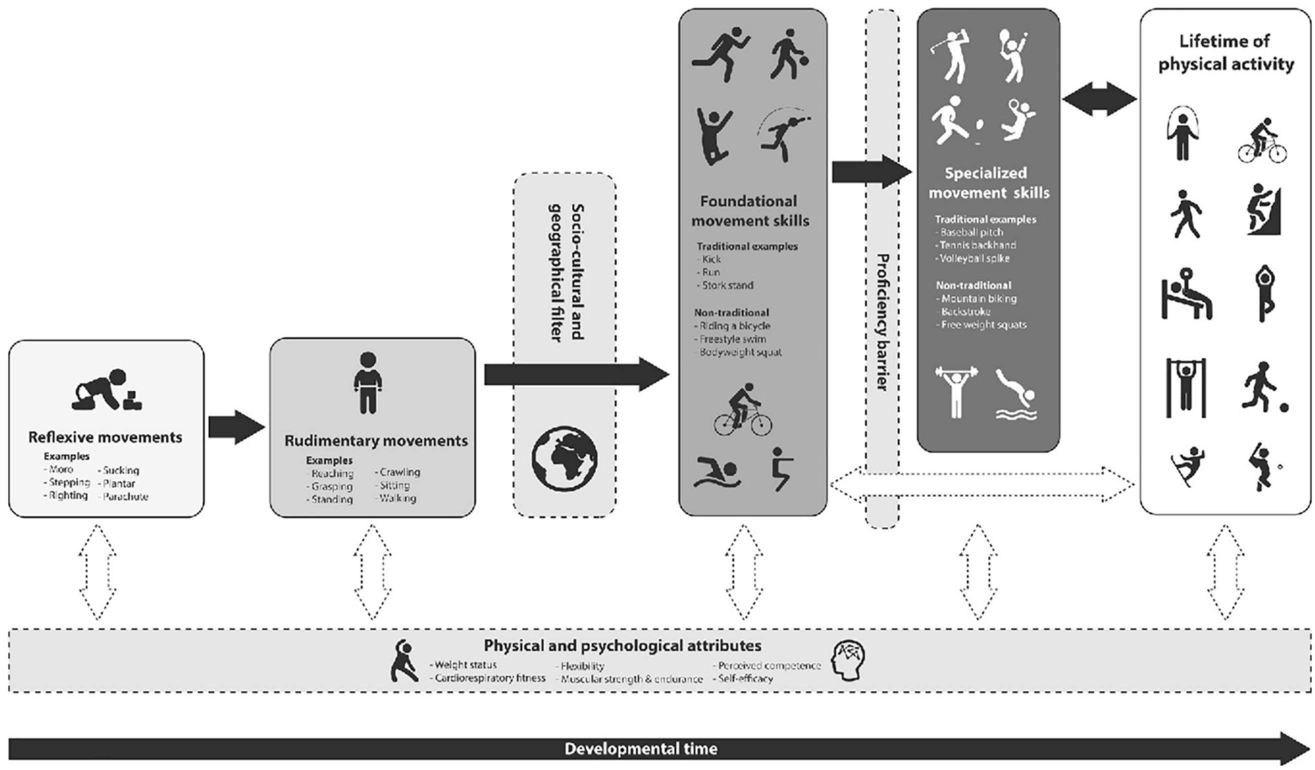

FIGURE 1 | Development of foundational movement skills supporting physical activity across the lifespan (Hulteen et al., 2018).

Ecological dynamics has been proposed as a framework to understand how we learn and acquire functional movement skills and how to create and structure enriched environments to support and cultivate a lifelong engagement in physical activity (Button et al., 2020). This perspective, espouses an embedded role for physical, cognition, emotions, and perceptual skills in the motor learning process. Ecological dynamics emerged from the work of Davids et al. (1994), Araújo et al. (2006), and Warren (2006) which highlighted multidisciplinary intersections between ecological psychology and dynamical systems theory. Ecological psychology suggests that learning movement skills is not predicated on processing information and accruing symbolic representations such as a movement template or schema, but rather on the continuous perceptual regulation of the learner's action in a learning context. From a dynamical systems perspective, functional movement solutions emerge from the interactions of multiple sub-systems within the person, task and environment (Thelen, 1989; Davids et al., 2008). All sub-systems spontaneously self-organize, or come together and interact in a specific way to discover and explore an efficient, effective, and functional movement solution for each specific task (Thelen, 1989; Davids et al., 2008). Children learn to perceive affordances at each moment, relative to their current intrinsic dynamics (including skill competence and cognitive development) in the current performance environment and for the current task (Adolph and Hoch, 2019). Furthermore, system changes involve a non-linear process, meaning that children do not acquire functional movement skills at a steady rate (Chow et al., 2016). A small, but critical change in one sub-system will cause a cascade across the whole system, resulting in the emergence of a new movement solution during exploratory activity (Davids et al., 2003; Chow et al., 2016). As a function of learning and experience, movement skills tend to stabilize in an attractor state within the dynamic system. In complex dynamic systems, learning results in synergy formation between system components, such as muscles, joints and limb segments, and synaptic connections in the brain, resulting in adaptations across the whole system to support a child, or adult, to thrive in their environment and seek out opportunities to be physically active (Chow et al., 2011).

In summary, learning involves constraints-induced synergy formation of physical literacy capacities (physical, cognitive, emotional, and perceptual) through exploration, invention and adaptation of action possibilities. For scientists, academics and practitioners observing children in their natural settings, it is important to understand how different types of constraints (related to the task, individual and environment) converge to enable synergy formation for utilization of affordances (i.e., opportunities or invitations for action in the environment; Pinder et al., 2011). Rich informal play environments is therefore essential for children's learning and development leading to a physically literate life. The next section will investigate how we can develop pedagogies and programs to maximize physical literacy for all.

MEANINGFUL ENGAGEMENT IN PHYSICAL ACTIVITY THROUGH THE LIFE COURSE: ECOLOGICAL DYNAMICS AND ENVIRONMENTAL ENRICHMENT

A key to sustainable engagement in physical activity is "enrichment": the design of a rich and varied range of athletic, participatory experiences, opportunities, challenges, and activities that will require skill adaptation (Button et al., 2020) across a practice landscape from generality – specificity (Woods C. T. et al., 2020). In the next sections, we suggest how enrichment in physical activity has been operationalized through an ecological dynamics rationale and has led to innovation of two contemporary learner-centered pedagogies, that employ non-linear principles of learning: Non-linear Pedagogy (NLP) and Athletic Skills Model (ASM), each of which reflects the inherent complexity involved in the learning process. Both pedagogical approaches emphasize the importance of enrichment experiences from an early age, and throughout the lifespan, to facilitate a generality, and later specificity of skill adaptation needed to engage in and maintain involvement in high performance sports through to recreational physical activities (Seifert et al., 2019; Stone et al., 2018; Strafford et al., 2018). As was the case for the learning of functional movement skills, "Enrichment" can be understood as an embedded approach to motor development and learning, emphasizing the importance of rich and varied possibilities to achieve task goals through interactions constrained by the body, task and environment (Renshaw and Chow, 2019). The learning interactions created through enriched environments lead to quality physical activity that will support adaptations to cognitive functions that, in time, have shown signs of transfer to support children's in academic achievement (Schmidt et al., 2017). To this aim, we shift the focus from "cool" executive functions, which are elicited under decontextualized and emotionally neutral conditions and studied from a cognitive perspective to "hot" executive functions, which are enacted in emotionally salient contexts and studied from a broader socio-emotional perspective of cognition (Zelazo et al., 2010). Such an understanding of cognition accounts for the non-linearity in cognitive development and fits with the individual's embodied/embedded physical literacy journey (Whitehead, 2001; Rudd et al., unpublished). This is encapsulated by Kelso et al. (2013) "*everyone's neural network is different. The nodes are different, the connections too, individual differences exist at all levels of structure and function. This means that children (or any human) will subtly walk differently, think differently and feel differently and critically respond to the environment differently.*" Therefore to support physical literacy across the lifespan where play opportunities have diminished we need pedagogies that account for such variability and individual difference in the learning process.

Non-linear Pedagogy

Ecological Dynamics have led to the creation of learner-centered pedagogical principles which cater for individual needs and emphasize an "explore–discover–adapt" learning approach called "NLP" (Chow et al., 2016). The predicted long-term effect of this pedagogical approach is that children will acquire a wide range of functional movement solutions that are both adaptable and attuned across physical activity environments (Chow and Atencio, 2014). Learning and practice are considered as a search for synergies such as functional performance solutions which are uniquely adapted to individual learners. Learners search to utilize "affordances" offered by the environment (Gibson, 1979). Affordances are opportunities or invitations for actions in the form of functional performance behaviors which can achieve specific intentions and goals, examples in sports and physical activities might include climbing a vertical surface (e.g., where affordances for support and traverse are offered by gaps, ledges and cracks in the surface of a tree) or intercepting a moving object (e.g., where the trajectory of a moving object invites an interception with one or more limbs, like the fingers, hands, arms, or legs). Continued experiences of interactions with objects, events, and significant others in a performance environment provide opportunities for learners to perceive and utilize new affordances, leading to adaptations of developing skills, enhancing performance functionality. Practice task designs for learners in sport and physical activity need to be coherent, innovative and challenging in order to *invite* specific patterns of behavior through the coordinated activity of learners. The aim of structured activity programs is to: (i) provide experiences and opportunities for individuals to enrich sub-systems which can help them perceive and utilize a broad range of affordances of a performance environment; and, (ii), engage in specialized learning experiences which can help them enhance their expertise in specific activities (Rudd et al., 2020).

Conceptual Model and Principles of Non-linear Pedagogy

Non-linear Pedagogy outlines five principles for the design of such practice tasks: *representativeness, constraints manipulation, task simplification, informational constraints, and functional variability* see Rudd et al. (2020).

The design of *representative* learning environments for individual learners requires a deep understanding of the information that regulates performance behaviors and the affordances that may invite specific functional actions needed to achieve intended task goals. Learning designs can be made more effective by including relevant information and affordances should emerge during the learning process. While *constraints manipulation* is critical in providing boundaries which afford specific movement possibilities for learners to exploit existing movement tendencies, there should be a clear focus on *task simplification* to enable learners to develop and maintain strong functional couplings between information and movement during learning. In practice, information is directly perceivable and is able to be picked-up by individual learners to constrain actions (Davids et al., 2008). Skillful perception is, acquired by a process of searching for "specifying" information used to regulate movements (Gibson, 1979). Learners should be allowed to *interact* with a performance environment (constantly make decisions and move) to generate more information that can be used for regulating subsequent performance. In this way,

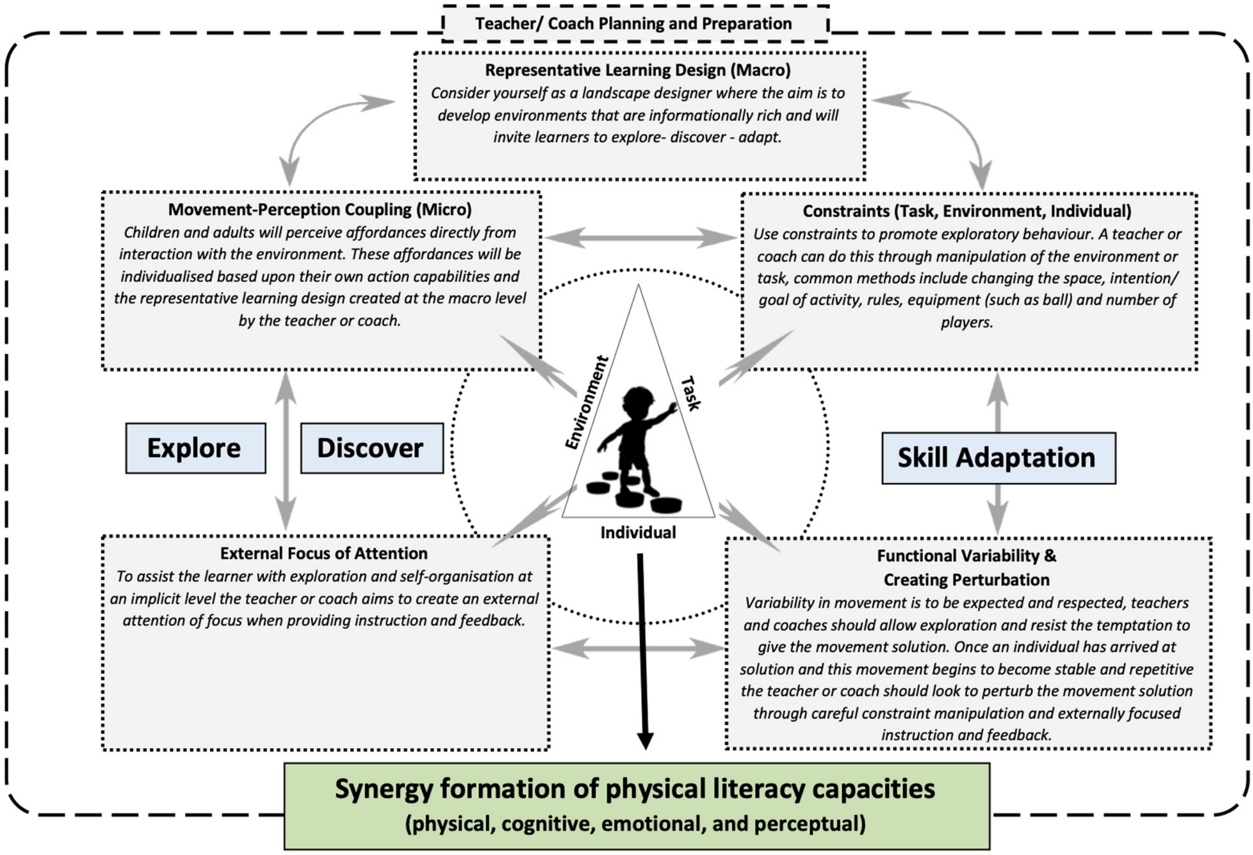

FIGURE 2 | Non-linear pedagogy principles and how they can support physical literacy.

learners can be sensitized to the impact that key *informational constraints* have on their emerging movement patterns. Practice variability plays a relevant role in challenging learners to explore different movement solutions and adapt their actions to the dynamics of information flows surrounding them in performance contexts (*functional variability*). A key challenge is to consider how to manipulate the amount of variability (in individual, task or environmental constraints) within, and between, learning sessions to challenge learners and enhance their self-regulatory capacities, rather than over-reliance on verbal directions from the coach or teacher (Chow et al., 2016). Below, we consider the effects of different directions of performance regulation on learners: known as global to local (coach-led) and local to global (learner-led) directions (Ribeiro et al., 2019). These design principles can operate through the key pedagogical channels of informational and practice constraints, with less attention being paid to verbal instructions to allow functional goal-directed behaviors to emerge in individuals.

A meta-analysis by Cerasoli et al. (2014) reported positive relationships between enjoyment and performance due to populations being intrinsically motivated to persist at a task. It seems that being intrinsically motivated in a physical activity is crucial for sustained participation and that the obsession with frequency-based movement metrics, such as time, amount (e.g., counting steps), and distance provides a limited view of experiences. Being learner-centered, NLP should support the satisfaction of the basic needs of autonomy, relatedness and competence and therefore nurture the development of motivation (Moy et al., 2016; Lee et al., 2017). Indeed, it provides the child with choice and freedom which may enhance their enjoyment and perceptions of autonomy. The respect the teacher or coach gives to the child's ability to explore, learn and problem solve may also enhance the child's feelings of relatedness (Lee et al., 2017). The focus on finding different movement solutions to achieve a goal creates a task oriented climate and should, over time, generate a shift in how the child views competence, away from an "ideal" movement performance toward functional, creative movements (Moy et al., 2016; Lee et al., 2017). Indeed, employing NLP to assist in the design of physical activity environments will foster novel functional movement solutions and generate new opportunities for exploration that trigger developmental cascades across physical literacy capacities (**Figure 2**). It should be noted, however, that while NLP could support basic psychological needs, it would reject the notion that motivation is intrinsic. Instead it would view motivation as residing beyond the boundaries of the human body in that outward facing intentionality, as a perception of surrounding information, is direct and an external focus of attention is key to achieving the intended task goals, harnessing embedded, self-organized, highly interconnected, co-dependent, behavioral sub-systems.

How Skill Adaptation Is Promoted in Non-linear Pedagogy: Should We Use the Term Creativity in Movement Performance and Do Executive Functions Matter?

A neurocomputational, top-down, account of creativity proposes that creative actions are specifically emanate from creative thinking and ideas. Aligned with this view, measures obtained with tests of movement creativity have frequently been used as movement-based measures of creative *thinking*, rather than measures of domain-specific movement creativity (Scibinetti et al., 2011). One of the main assumptions in accounts of the neural underpinnings of creativity, is that tasks involving creative thinking induce changes in prefrontal cortical activity (Dietrich and Kanso, 2010). The rationale behind this perspective is that, since the prefrontal cortex is the main substrate of executive function, the relationship of creativity to core executive functions (inhibition, working memory, cognitive flexibility) is key. In particular, the prefrontal cortex is proposed to activate executive processes relevant to the ongoing task and to the goal-oriented expression of creative insights (Dietrich, 2004). The postulate, that executive control is needed prior to enacting a creative idea in the motor domain, has been challenged by recent evidence that the manipulation of working memory load does not affect the conduct of convergent and divergent tasks typically used to test motor creativity (Moraru et al., 2016; Orth et al., 2019). Processes like working memory, which is seemingly not crucial for a creative movement action to emerge, may exemplify "cool" executive functions that are assessed under decontextualized, emotionally neutral task conditions.

In recent years, an embodied/embedded view of cognition, grounded on sensorimotor coupling, and subserving action (Engel et al., 2013) and has provided the basis for a new perspective that brings creativity research closer to an ecological dynamics framework. Orth et al. (2017) proposed that creative actions are novel functional movement patterns that do not need the top-down, antecedent generation of a creative idea, but rather emerge in a bottom-up fashion from the exploration of adaptive solutions to motor problems.

Creativity, captured from an ecological dynamics rationale, is posited as a transformational process, involving, search, exploration and discovery of novel and functionally efficient behaviors for performance (Hristovski et al., 2009). In this view, movement output emerges from cooperating subsystems, exploiting self-assembly tendencies to form synergies at different levels, concomitantly self-organizing with other subsystems to achieve functional movement solutions (Raja and Anderson, 2019). This creative process in the context of coordination and its acquisition in athletes and sports teams is predicated on the continuous (re)formation of functional synergies between relevant system degrees of freedom during practice and performance (Woods C. et al., 2020). Ribeiro et al. (2019) highlighted how system degrees of freedom in athletes and sports teams are continuously (re)emerging in and out of synergies adapted to achieve movement goals and tactical behaviors. They proposed two main directions for synergy (re)formation in sport practice: global to local (synergy formation directed by an external agent such as coach or teacher) and local to global (when players self-organize under competitive performance constraints). These directional tendencies for self-organization of system degrees of freedom rely on a broad array of task and environmental constraints that must be perceived to effectively explore available opportunities for action.

During movement skill performance the inherent self-organization tendencies of subsystems is predicated on degeneracy and multistability (Edelman and Gally, 2001; Diamond, 2013). NLP appreciates the role of neurobiological properties of self-organization, degeneracy and multistability, ensuring that adaptive movement variability is an essential ingredient of physical activity, movement experiences and task practice to facilitate innovation in synergy formation (Hristovski et al., 2009; Chow et al., 2011). An observed output from the continuous adaptation of actions under changing constraints are movement innovations, emerging through interactions with the environment, task and individual constraints. In this ecological dynamics conceptualization, executive functions play an integral role in planning and preparation underpinning the intentionality, and "knowledge of" the environment (Woods C. T. et al., 2020) that frames the self-organization tendencies that emerge under interacting constraints. The deeply entwined relations of intentions, perception and action provides a boundary for the self-organization tendencies that can be exploited for the functionally innovative and adaptive actions during the continual transitioning between environmental information and the intrinsic dynamics in sport performance (Fajen et al., 2009; Hristovski et al., 2011; Araújo et al., 2019; Seifert et al., 2019).

How can these ecological dynamics concepts be exploited in competition and sport practice? Santos et al. (2016) proposed a game-centered, constraints-led approach as a means to promote the emergence of innovative and adaptive tactical behaviors in team sports practice. Further, during competitive performance the intentionality is to "*win or beat an opponent*" such a strong outward facing intentionality may be necessary for players to learn, within competitive situations will lead to perturbation and require self-organization by continuously adapting to dynamic performance constraints (Ribeiro et al., 2019). To support the emergence of local to global tendencies in competitive performance, researchers and practitioners could manipulate task and environmental constraints and evaluate the impact on aspects of physical literacy development as well as whole team synergies. Buszard et al. (2016) conducted a systematic review of equipment manipulations and play space in children's sport and found that these adjustments to task constraints are advantageous to performing functional movement skills, compared to traditional global to local methods (teacher led). García-Angulo et al. (2020) found that manipulation of task constraints such as varying the pitch size, number of players or goal size enhanced football-specific self-efficacy. Buszard et al. (2017) found that an overemphasis on global to local instructions can be detrimental to children who have lower working memories, inhibiting their motor learning. This is, in turn, consistent with findings showing an advantage of global attention training for enhancing creative tactical solutions (Wyrick, 1968) and the special ability of highly skilled team players in using a global attentional focus (Pesce and Bösel, 2001) and performing local-to-global visual attention shifts (Pesce et al., 2016). The relevance of local to global practice designs in sport performance contexts suggests a novel intersection of key ideas in NLP with the less investigated subset of "hot" executive functions, the motivational salience of the context and emotional engagement as a distinguishing feature of "hot" executive functions for harnessing self-organization tendencies (Harms et al., 2014). NLP, applied to programs of work on team sports appropriately fosters "hot" decision making, underpinning a rapid synergy formation process amongst system components, and exploiting a "local to global" directional tendency within individual players and teams (Davids et al., 2013; Ribeiro et al., 2019) predicated on individual physical literacy. The key tenets of ecological dynamics, and its related principles of an NLP, are harmoniously aligned with ideas of a practitioner model of skills development and learning, such as the ASM, which we discuss next.

Athletic Skills Model

Traditionally organized physical activity, sport and physical education programs have been criticized for being overly structured, prescriptive and didactic in their organization and delivery (Kirk, 2010; Jess et al., 2017) which may cause negative perceptions and associations between children and physical activity and put children off physical literacy (Ntoumanis et al., 2004; Whitehead, 2010). This is problematic as participation in organized programs affects children's engagement in on-going autonomous physical activity (Morgan et al., 2008). Such negative perceptions have also been noted with traditional pedagogical practice designs, emphasizing frequency-based metrics, such as number of hours spent in practice and implicated in high dropout rates recorded from development programs for talented youth athletes in high performance sports (Côté et al., 2011; Coutinho et al., 2016). The ASM is a pedagogical framework that offers an alternative program structure which emanated from professional sports practice, proposing how a diverse range of sport experiences can enrich later specialization in a sport (Wormhoudt et al., 2018). In this respect, it is an ideal contrast to models of early specialization, such as the deliberate practice approach. The ASM focuses on the development of functional movement skills and physical literacy capacities, advocating that early childhood play and practice experiences should involve participation in "multi-sports," involving a diverse range of movement experiences and activities. In the "multi-sport" stage of the ASM, children need to experience and "sample" a broad variety of activities and sports which will enrich their athletic development, encouraging them to explore functional movement behaviors that enhance all their physical literacy capacities.[see **Figure 3**; (Kirk, 2005; Côté and Hancock, 2016)].

The holistic development of learners, when interacting with different fields of a performance landscape, contributes to their functional co-adaptation to changing environmental and task constraints (Araújo et al., 2010). A key aspect of learning design in the ASM is that activities should always involve pleasure and fun experienced through the constant exploration of different movement environments leading to novel individual action possibilities. Through play in different performance contexts, engagement in multiple sports and physical activities has the potential to increase the long-term motivation for practice, essential for later performance in elite sports, should learners want to continue to the highest performance levels (Wormhoudt et al., 2018). As mentioned earlier, an ecological dynamics rationale highlights that a major problem with early specialized, sport-specific training concerns the ubiquitous over-emphasis on specificity of transfer in practice at all levels, which is especially problematic for the physical and mental health of youth and children (Davids et al., 2017). The frameworks of ecological dynamics and the ASM provide a more nuanced understanding of transfer from training to performance in sport. It is suggested that the role of behavioral enrichment, conferred by *generality of transfer* has typically been misunderstood and undervalued in athlete development programs.

The Role of Multi-Sports and Donor Sports in Athlete Development

The ASM is a practitioner-led model of talent development and skill acquisition, proposing how, through "multi-sport" (rich, varied) experiences, movement competences can support transfer of five relevant performance components: agility, endurance, flexibility, power and stability. The ASM proposes that perception and action is organized into seven distinct abilities: adaptability, coupling ability, ability to react, rhythmic ability, balance ability, spatial orientation ability and the kinetic differential ability (Wormhoudt et al., 2018). These performance components and related abilities are, not only extremely relevant for developing skill and expertise in talented athletes, but also for recreational-level engagement, and maintenance of participation, in sport and physical activity throughout the lifecourse. The ASM clearly articulates that, early in learning, children should experience fun and enjoyment in *playing* a variety of physical activities and sport, which may not have a direct relationship to a target sport (Wormhoudt et al., 2018). Here, the central argument is that individuals become skillful by being exposed to a mix of non-specific and specific experiences, which support more functional capacities for later specialization in a specific target sport (Güllich, 2017). Integrating the key concepts of the ASM and the Ecological Dynamics approach to motor learning, thereby avoiding the consequences of early specialization, it is proposed that *Donor Sports* can enrich foundational skill development, relevant for later performance in a target sport (Savelsbergh and Wormhoudt, 2019). Opportunities to acquire relevant, athletic skills and abilities, such as balance, body awareness, coordination, reaction speed, strength and turning ability, can be "*donated*" through an affordance landscape shared between an athlete's main target sport and donor sport activity (Strafford et al., 2018).

Sport practitioners should aim to integrate donor sports, into teaching and coaching programs, at all levels, to exploit the sharing of foundational movement skills required for an

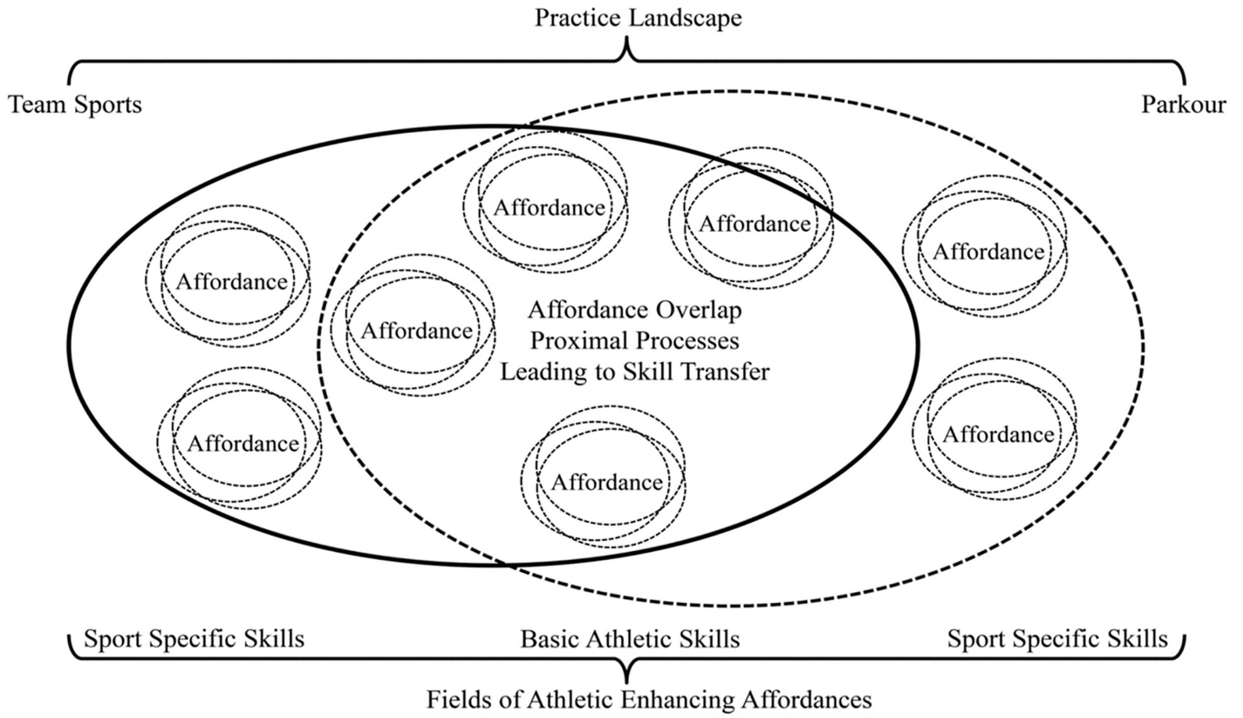

FIGURE 3 | Overlap of performance-enhancing affordance fields between team sports and parkour as a donor sport (Strafford et al., 2018).

athlete to perform *well* in a target sport. Being exposed to donor sports early in learning could be particularly useful when particular skills required in a target sport, are considered to be under-developed in an individual athlete's movement repertoire. Shared performance-enhancing affordances in the donor sport landscape present opportunities for the development of key athletic skills that may be instrumental for specialization in an identified target sport. For example, in team sports donor sports exposure may enhance skill transfer in the way that performance in both sports requires the dynamic (re)organization of body segments relative to the opposition, task goal [e.g., specific postural control and balance required for movement orientation and (re)orientation when challenging for the ball in team sports such as soccer and rugby]. This needs to be verified in future empirical research. Therefore, a challenging issue for researchers and practitioners concerns how to enhance the specificity of skill transfer through a donor sport which is representative of the functional coordination patterns shared with a target sport. Evidence suggests that donor sports may also be beneficial for the development of psychological skills, such as problem solving; stress relief; self-efficacy and risk management (see Strafford et al., 2020).

The Athletic Skills Model's Emphasis on the Importance of Physical Activity Enrichment

Using donor sports to enrich the performance of learners in sport and physical activity provides the basis of how the ASM emphasizes the value of enrichment through experiencing a wide range of activities. In this section, we exemplify how the ASM's advocacy of the role of donor sports has implications for how affordances landscapes in sports such as Parkour and Futsal can support skill development in team game players.

Parkour

Practitioners (known as Traceurs) are required to negotiate environmental properties and features of indoor or outdoor installations in the most innovative and efficient manner possible. Parkour's two main distinctive disciplines are speed and free-style. Speed runs require Traceurs to move from a start to an end point in the quickest way possible, and free-style runs are judged on how creative the Traceurs are at moving around the installation. Parkour's potential as a donor sport for athlete development has been recognized recently (Strafford et al., 2018, 2020). In team sports, practice designs encourage performers to effectively use dynamic and fluid movement patterns in representative game-based scenarios, with the dynamic (re)organization of body segments at different speeds, relative to movement of the ball and positioning of opponents in the surrounding landscape (Edwards et al., 2017; Seifert et al., 2019). Strafford et al. (2018) outlined how Parkour could provide an adaptive and affective platform for psychological, perceptual, physical and social development in team sport players. They proposed that Parkour style activities should be integrated into the athlete practice landscape to develop athleticism and skill transfer in youth team sports, such as soccer and rugby, through a shared network of affordances and foundational performance behaviors. A shared network of affordances in the environment may invite movement exploration, which in turn provides opportunities for the development of athletic skills relevant to the team sport game being targeted. In this sense, abilities that are deemed to be critical to athlete specialization in team sports can be "donated" by Parkour, such as creativity in negotiating gaps or obstacles, fluidity of movement and related decision-making or safe landing strategies.

According to the ASM, a coach facilitates the development of practice landscapes (Wormhoudt et al., 2018). Strafford et al. (2020) interviewed experienced Parkour Traceurs on the skills they believed were developed through parkour, also asking how they developed Parkour practice landscapes to support the development of physical, perceptual, psychological and social skills. Parkour Traceurs explained that, for athletic development, indoor parkour environments have to promote creative and exploratory movement behaviors, whilst physically and psychologically conditioning the athlete, through heightened opportunities for decision making and action functionality. Practically, Parkour Traceurs discussed how this is often achieved through the development of modular practice landscapes, where the spacing, orientation and angles of the installation blocks and bars set ups are manipulated to increase or decrease task difficulty.

The ideas outlined by Strafford et al. (2018, 2020) suggest that the development and design of playscapes require a fundamental and direct shift toward the inclusion of varied boundaries, limitations and features not typically found in modern playgrounds, which constrain the (re)organization of motor system degrees of freedom and different levels relative to each individual's intrinsic dynamics (Bernstein, 1967; Sparrow and Newell, 1998; Sharma-Brymer et al., 2015). Parkour-style activities like "world-chase tag" could provide a platform for integrating Parkour playscapes into team sport settings[1]. For example, the global constraints governing world-chase tag (i.e., the first person to tag their opponent wins) are comparable to the offensive phases in Rugby Union, where to regain possession of the ball and score a try, athletes have to couple their movements relative to the positioning of their opponents, teammates and the direction of the ball.

Futsal as a donor sport for football

Futsal places a clear emphasis on controlling and manipulating the ball in a smaller relative space per player (RSP), compared to other team sports, like football and rugby. In futsal, performers require "soft feet" to manipulate the ball into tight spaces, using different segments of the foot, to dribble, pass and shoot the ball [which is smaller (size 3), and a lower coefficient of restitution than a regulation size 5 football ball; Araújo et al., 2004]. In this sense, futsal is distinct from football, with the latter's emphasis on performance of gross motor skills and increased playing area dimensions (with associated differences in timing and coordination of actions). For this reason, footballers are required to have greater levels of relative strength and explosive power to move around larger pitch areas efficiently (with and without the ball), requiring coordination and dynamic (re)organization of body segments in relative space. With different playing area dimensions on a macro level (in terms of goal directed actions, goal scoring, covering space), futsal, on a micro level, promotes the development of skills required to perform *well* in some contexts of football, such as: balancing to react to sudden changes of direction on court, coordination for changes of direction and the capability to react quickly and rhythmically for the smoothing of perturbations. Further, similar to football, futsal requires performers to couple their body movement precisely with movements of teammates and the opposition, and the direction of the ball, through visual exploratory behaviors (known as "scanning" in team sports performance). Indeed, Oppici et al. (2017) observed that futsal players scanned for space and co-positioning of other players 54% of the time prior to taking the first touch, compared to 16% of the time in football players. Futsal also provides more frequent opportunities to perform skills and engage with the ball, compared to 11 a side football (Davids et al., 2013). In football and futsal, each player is required to use both feet to perform the skills needed during competitive performance, as well as to engage in collective tactical behaviors, with and without the ball (Travassos et al., 2018). Preliminary evidence suggests that the performance landscape shared between futsal and football implies that the former can act as a donor sport to enrich athletic skills relevant to the behavioral adaptability that footballers can exploit for skill transfer. Integrating futsal into football practice, could lead to enriched physical, perceptual and psychological skills, by emphasizing behavioral correspondence between the sports, and heightened behavioral adaptability developed by exploiting similarities in intentional constraints on performance (Seifert et al., 2019) although this needs to be substantiated in empirical research.

AN EMERGING DISCOURSE FOR PHYSICALLY ACTIVE FUTURES: PHYSICAL LITERACY AND HOW IT ALIGNS WITH AN ECOLOGICAL DYNAMICS RATIONALE

We began this paper by highlighting a concern with the current direction of physical activity research and the professionalization of children's sport, and proposed an ecological dynamics rationale as an alternative discourse that focuses upon enrichment activities for each individual across the life course. These ideas lead us to consider physical literacy, a concept put forward by International Physical Literacy Association (2017) who defined physical literacy as "*the motivation, confidence, physical competence, knowledge and understanding to value and engage in physical activity for life*." Over the last decade, the concept of physical literacy has gained traction in physical education, youth sport literature for the holistic development of physical, perceptual and cognitive skills to support long term engagement in physical activity (Sullivan et al., in press). Historically, physical literacy discourse emanated from physical education, in particular movement education literature, underpinned by the philosophy of phenomenology which contends that every individual has a unique embodied understanding of the world. This is embedded within their own experiences with the physical and mental being viewed as an

[1] https://www.youtube.com/watch?v=Ea_Mkmj92PY

indivisible, mutually enriching whole (Shearer et al., 2018). In recent times the concept of physical literacy has been found to be appealing to many, though it has been highlighted that the philosophical underpinnings are considered by many to be overly complex (Jurbala, 2015; Shearer et al., 2018). There are also claims that it is difficult to operationalize, leading to governments, policy makers, researchers and practitioners developing their own interpretations of physical literacy (Martins et al., 2020). Up to this point we have demonstrated that linking the ecological dynamics rationale and physical literacy can support long term engagement in physical activity through the integration and the adoption of NLP and ASM across physical education, sport and exercise context. The final section of this paper will demonstrate how ecological dynamics can provide a way to measure physical literacy which is one of the current most contentious issues facing the adoption of physical literacy.

A common misconception within physical literacy is the adoption of fundamental movement skills to capture children's physical literacy (Rudd et al., 2019). Children perform skills in isolated and closed environments and are assessed on how well they conform to an optimal movement template (Ulrich, 2013; Rudd et al., 2016). This over-emphasis on technique is driven by the level of standardization required to make reliable comparisons across cohorts of children when using kinematic, process-oriented assessments. This data collection is vital as it is responsible for shining a light on the current poor levels of movement in children globally. However, when it is conceptualized from a physical literacy vantage point it is fraught with validity issues, from both a phenomenology philosophy perspective and from the ecological dynamics rationale (Araujo and Davids, 2009; Almond, 2014; Rudd et al., unpublished). An over-emphasis on technique diminishes perception and action of how children play in the game situation or in unstructured environments. This is critical, as in closed environments the self-organization of physical literacy capacities will be very different from the embodied experience of playing with friends.

Utilizing an ecological dynamics conceptualization of physical literacy, we can move toward a better, though still not perfect (in this paper anyway), solution to this conundrum, by utilizing an assessment which is both reliable and a valid measure of physical literacy. To develop a reliable movement assessment we require a standardized environment and task for all children; ecological dynamics requires the task to be outward facing in an open and informationally rich environment that is safe for exploration (Seifert et al., 2019; Hacques et al., 2020). There are already movement assessments being used that, whilst not developed from an ecological dynamics framework perspective, meet these requirements, for example the divergent movement assessment (Cleland, 1990; Rudd et al., 2020). Children are placed in a rich environment that has been set up based on a standardized protocols, in that every child is placed in the same environment and given two 90 s blocks to explore and interact with the environment in as many ways as they can. For each functional movement solution they demonstrate, they are rewarded with a score of one and to assist children with exploration, every 30 s children receive a predefined prompt from the research assistant. In summary, such a task does not prescribe a technical movement skill template but instead provides an inviting/enriched environment for children to interact and perform in. With a standardized environment and carefully considered task constraints it will be possible to gain an understanding of the invitations for action (affordances) which emerge that are functional for that child. Using this form of assessment a child in a wheelchair can demonstrate a far greater number of functional movement solutions based upon their own self organization constraints into functional movement solutions than a child who is performing on two feet but has had a poorer physical literacy journey to that point. This is because this assessment taps into the children's exploration and displays how far they have come in terms of learning to learn how to move (Adolph and Hoch, 2019). This assessment is individualized and closer to the embodied experience in play (though again not perfect) and can be used to create established normative and group comparisons for a child's physical literacy. This can support researchers in monitoring skills and practitioners in designing learning environments which support physical literacy using pedagodgies such as NLP and ASM.

CONCLUSION

This paper provides applied scientists and practitioners with a new perspective on how to improve the quality, not just the quantity, of participation in sports and physical activity to enhance the health and well-being of future generations. It has proposed a shift away from reductionist approaches to suggest that humans can be conceptualized as deeply integrated complex systems. An individual's, interaction with a task and their environment, through meaningful engagement in physical activity results in the performance of functional movement solutions and adaptations through the whole system (physical, cognitive, emotional, and perceptual). These adaptations across the whole system are advantageous in supporting children and adults on their journey to lead a physically literate life. Furthermore, an ecological dynamics rationale can provides a framework to support physical literacy program design using NLP (Chow, 2013) and the ASM (Wormhoudt et al., 2018) as well as highlighting the benefits of assessments such as the divergent movement assessment in measuring physical literacy compared to more controlled assessments such as the test of gross motor development (Cleland, 1990). Combining these enrichment experiences from an early age and throughout the lifespan, utilizing contemporary theory of skill acquisition, offers real hope to engage and maintain childrens' and adults' involvement in sports and physical activities across the lifecourse (Seifert et al., 2019; Stone et al., 2018; Strafford et al., 2018) with the ensuing health benefits.

AUTHOR CONTRIBUTIONS

JR and KD conceived the review. All authors were involved in the writing and revising of the manuscript and read and approved the final manuscript.

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Rhythmic Physical Activity Intervention: Exploring Feasibility and Effectiveness in Improving Motor and Executive Function Skills in Children

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Introduction: Increasing literature has emerged investigating the importance of considering the qualitative characteristics of physical activity (PA) interventions and sports as well as considering the role of motor competence in the exercise–cognition interplay. The purpose of this pilot study was to examine the feasibility and effectiveness of a rhythmic PA intervention compared to a standard physical education program, on motor and hot and cool executive function (EF) skills.

Methods: Children ages 6–11 were enrolled in one of the two programs: a rhythmic program (n = 22) and a physical education program (n = 17), both meeting for 30 min, twice per week, for 7 weeks. The rhythmic program emphasized moving to the beat of music and moving in various rhythmic patterns with whole body movements, clapping, and drumsticks. The children also created their own rhythmic patterns and socially engaged with other children by working in pairs and sharing their routines with the group. The physical education group engaged in ball skills, locomotor patterns, team sports, and moving through stations in small groups, with no emphasis on rhythm. Pretest and posttest measurements included measurement of balance (Movement ABC-2), cool and hot EF (Flanker, SWAN), and social factors, whereas throughout the implementation period data on affective valence, enjoyment, cognitive engagement, perceived exertion, and PA levels were collected at every lesson in both groups.

Results: The rhythmic program used in this study was feasible, scalable, affordable, and able to be implemented with minimal preparatory time. Children in both groups (rhythmic and physical education) engaged in a similar level of PA and had similar positive experiences from the programs. Both groups improved in balance and cool EF, and there were significant correlations in the change scores between balance and cool EF, as well as between cool EF with hot EF and socio-emotional factors.

Discussion: This study contributes to the literature by exploring the potential value of rhythmic programs as a vehicle in helping children develop motor and EF skills while deriving joy and positive social interactions from the program.

Keywords: chronic exercise, executive processing, physical education, cognition, social, enjoyment, youth

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INTRODUCTION

Promotion of physical activity (PA) in youth is acknowledged as a priority by many prominent public health organizations in the United States (Centers for Disease Control, and Prevention [CDC], 2010; Institute of Medicine [IOM], 2013). Organizations have emphasized the need to include more PA throughout the school day, with physical education as a central component in the implementation of Comprehensive School PA Programs (Centers for Disease Control, and Prevention [CDC], 2010; Institute of Medicine [IOM], 2013; Shape America, 2014). The ASCD (former Association for Supervision and Curriculum Development), a leading educational agency, in collaboration with the CDC adopted a joint goal to promote learning and health through the whole-school, whole-community, whole-child model (ASCD and Centers for Disease Control and Prevention [CDC], 2014). The ASCD's Whole Child Initiative views the collaboration between learning and health as fundamental, emphasizing the need to shift the focus from narrowly defined academic achievement to one that promotes long-term development and success of children (ASCD and Centers for Disease Control and Prevention [CDC], 2014).

Compelling evidence demonstrates that PA is associated with improvements in both cognitive function and academic performance (e.g., Mura et al., 2015; Donnelly et al., 2016), which is supported by research describing the interconnection between motor and cognitive functions in children (e.g., Diamond, 2000; Van der Fels et al., 2015). Evidence indicates, however, that not all forms of PA benefit cognition equally (Diamond and Lee, 2011; Pesce, 2012; Diamond, 2015; Pesce and Ben-Soussan, 2016; Vazou et al., 2019b), and it has been suggested that "the degree to which the exercise requires complex, controlled, and adaptive cognition and movement may determine its impact on executive functions (EF)" (Best, 2010, p. 336). Researchers have argued that children who perform activities that are not challenging because of lack of progression in task difficulty do not challenge EF (Diamond and Lee, 2011) and that when instructional methods challenge learner's thoughts and actions, cognition is enriched and maintained (Tomporowski and Pesce, 2019). Thus, there are likely a number of contextual factors, including instructional techniques, intervention content and structure that impact the degree to which a PA intervention improves EF.

A recent review and meta-analysis on different characteristics of PA (i.e., aerobic, motor skills, cognitively engaging activities, and all combinations of those facets) supported the significant positive effect of PA interventions on EF (0.46 effect size) and identified differences between the categorically different long-term PA interventions (Vazou et al., 2019b). However, as several researchers have suggested, the quantitative and qualitative characteristics of PAs, as well as unique elements within a PA program (e.g., type of movement, mental resources, skill acquisition, emotional activation) and contextual factors (including the physical and the social environment) may impact the effectiveness of those interventions (Tomporowski and Pesce, 2019; Vazou et al., 2019b). As Diamond (2015) recommended, the most effective interventions are likely those that, "(a) train and challenge diverse motor and executive function skills, (b) bring joy, pride, and self-confidence, and (c) provide a sense of social belonging (e.g., group membership) (p. 963)." Moreover, interventions may differentially affect two types of EF. "Cool EF" are those exhibited in "decontextualized and affectively neutral conditions" (Pesce et al., 2020), such as working memory, inhibition, and strategy use, while "hot EF" involve cognitive and emotional control in "contexts that generate heightened emotion" (Pesce et al., 2020), such as playing a game and making decisions in an emotionally charged environment. This research points to the importance of studying contextual factors associated with diverse PA interventions.

From a practical standpoint, PA interventions that are designed for youth also should consider the natural desire in children to explore new movements and skills. PA programs should challenge children using a wide variety of activities that focus on motor skill development and variability of practice (Myer et al., 2016; Pesce et al., 2019), while simultaneously providing the novelty and variety necessary to sustain interest and enjoyment (Sylvester et al., 2018). Positive affect and enjoyment predict PA behavior (Cox et al., 2008; Nasuti and Rhodes, 2013) and have been proposed to be associated with higher levels of engagement and self-regulatory skills (Isen and Reeve, 2005; Diamond, 2015; Brand and Ekkekakis, 2018). Recognizing the importance of engagement, National Standards in the United States (SHAPE America) include a physical education goal of providing enjoyable and varied PA that also enhances children's motor skill development.

Tomporowski and Pesce (2019) highlighted common processes involved in PA and the performing arts that may benefit cognition. PA programs with a rhythmic or music component, such as dance or drumming, are hypothesized to improve EF (e.g., Diamond, 2014), as rhythmic movements challenge both cognitive and motor systems. They require mental effort to move with the tempo and require learning new rhythms and accompanying movements. However, little research has focused on the cognitive benefits of combining music and PA in an integrated intervention. Lakes et al. (2019) described expressive or rhythmic movement as having the potential to extend both the beneficial effects of music and PA, positing that music and movement interventions can provide multisystem learning opportunities characterized by embodied cognition. The embodied cognition perspective describes cognitive processes as embedded within the ways in which we interact within the world (Wilson, 2002), and cognitive improvements are likely strengthened when trained in such a context. Preliminary studies examining rhythmic PA programs and cognition include research by Lakes et al. (2019) examining the Creatively Able program (an intervention involving music, dance, and the engagement of children in creating choreography) in children with promising findings related to children's engagement, enjoyment, and cognitive functions. Similarly, an intervention with music education was found to positively affect EF skills and academic achievement (through the mediating role of EF) in typically developing elementary children (Jaschke et al., 2018). More research on interventions with these features is warranted.

This pilot study was designed to evaluate the feasibility and effectiveness of a novel rhythmic PA program compared to a generalized physical education program, on motor and cognitive skills in children. We examined several qualitative and contextual features of the rhythmic PA program and their possible association with motor and cognitive skills. This feasibility study was designed to help researchers and practitioners determine whether a rhythmic intervention should be recommended for evaluation on a larger scale and potentially implemented as a PA program for youth during physical education or after-school. Our study goals were consistent with those recommended in intervention literature that emphasize the importance of early examinations of the feasibility of new interventions with a focus on acceptability, demand, implementation, practicality, and limited-efficacy testing (Bowen et al., 2009).

MATERIALS AND METHODS

Recruitment and Participants

A total of 39 children, ages 6–11 [*M* age = 7.69 ± 1.52 years; 21 males (53.85%)], participated in this study, with 22 in the rhythmic group and 17 in the physical education group. **Table 1** includes the demographic characteristics of the participants in each group. The physical education group was recruited through a physical education program for homeschooled children offered through a university course by the lead researcher. The Rhythmic group was recruited from community advertisements and the university email list for faculty and staff. In addition to age, inclusion criteria were the parent's ability to consent in English and the child's ability to assent in English. Exclusion criteria included a DSM-5 diagnosis other than Developmental Dyslexia or Attention Deficit Hyperactivity Disorder (ADHD), an IQ below 80, or parental report of a history of developmental disability, intellectual disability, or brain trauma. **Figure 1** shows the CONSORT flow diagram of enrollment for both groups. A total of 47 children were initially recruited, 17 in the physical education group and 30 in the rhythmic group. Six participants dropped out before the implementation due to scheduling conflicts, and two participants dropped out due to illness; all eight were enrolled in the rhythmic group. The study was approved by the university Institutional Review Board. Written informed consent and verbal assent were collected from parents and children, respectively.

Measures

Baseline Measures

For demographics, weight and height were measured privately with a body scale and a stadiometer. Body mass index was computed by dividing weight (in kilograms) by the square of height (in meters).

The Kaufman Brief Intelligence Test—Second Edition (KBIT-2; Kaufman and Kaufman, 2004). The KBIT-2 Non-Verbal Section is a measure of non-verbal intelligence (non-verbal IQ). Children select the picture on a flip card that best fits the matrix pattern pictured on the card. The matrices become progressively difficult, and when three consecutive mistakes occur, the test is stopped. Standardized scores are calculated based on United States norms for a given age group.

The Cardiovascular Endurance Fitness—PACER FitnessGram (4th edition; Plowman and Meredith, 2013) was administered in the gymnasium with a group of children. A black line and cones at the two ends of the gymnasium were used to mark the 20-m distance used for the task. The children were asked to line up at the start and to begin running from one side to the other following the prerecorded auditory signal, which becomes progressively faster. Children were asked to keep up with the cadence and stop when they can no longer keep up with it. The numbers of cycles each child completed were recorded by research assistants observing the test.

Pretest and Posttest Measures

The Movement Assessment Battery for Children-2 (M-ABC-2; Henderson and Sugden, 2007) balance subtest was administered individually. In this subtest, there are three tasks: (1) balancing on one foot on a balance board for up to 30 s (one trial on each leg), (2) walking on a line using tandem foot placement without stepping off the line for a maximum of 15 steps (2 trials), and (3) hopping in a controlled manner up to 5 continuous hops on a series of preplaced squares (2 trials). The scores are standardized so that a single subtest score is calculated and analyzed.

A modified version of the Rhythm/Beat Competence Assessment (Weikart, 2006) was administered individually. In this assessment, children were instructed to tap a pair of drumsticks together to the beat of the song. Children then listened to a standard song and tapped to the beat until the song ended, for a total of 64 beats. Observers measured rhythm/beat competence as the total number of times the tap matched the beat, with a maximum score of 64.

The Strengths and Weaknesses of ADHD-symptoms and Normal behavior (SWAN) rating scale (Swanson et al., 2012) was completed by parents to measure two factors: Attention (9 items; e.g., "sustain attention on tasks or play activities") and Behavioral Control [9 items; e.g., "settle down and rest (control constant activity)]." The scale is appropriate for use from preschool age and beyond (Lakes et al., 2012). Each item is rated across a dimension using a seven-point response scale, ranging from "far below average" (rated in this study as 1) to "far above average" (rated in this study as 7). Cronbach's alpha coefficients of internal consistency in the present study were acceptable, for both Attention ($\alpha = 0.84$, $\alpha = 0.85$) and Behavioral Control ($\alpha = 0.91$, $\alpha = 0.89$, for pre and posttest, respectively).

For EF, the computer version of Flanker Fish test (using Presentation software; Neurobehavioral Systems, 2012) incorporates the Standard Flanker (inhibition), Reverse Flanker (inhibition and working memory), and Mixed Flanker (inhibition, working memory, and cognitive flexibility) conditions, specifically modified for children (Diamond et al., 2007). In this computer version of the Flanker test, there are five fish shown and the child must "feed" the hungry fish by pressing the left or right key on the touch-screen, depending on which direction the target fish is/are facing. In the Standard Flanker task (17 trials), the fish are blue and the target fish is the middle one, requiring participants to inhibit attention to the fish positioned on either side. In the Reverse Flanker task (17 trials) that follows, the fish are pink, and the target fish are all but the

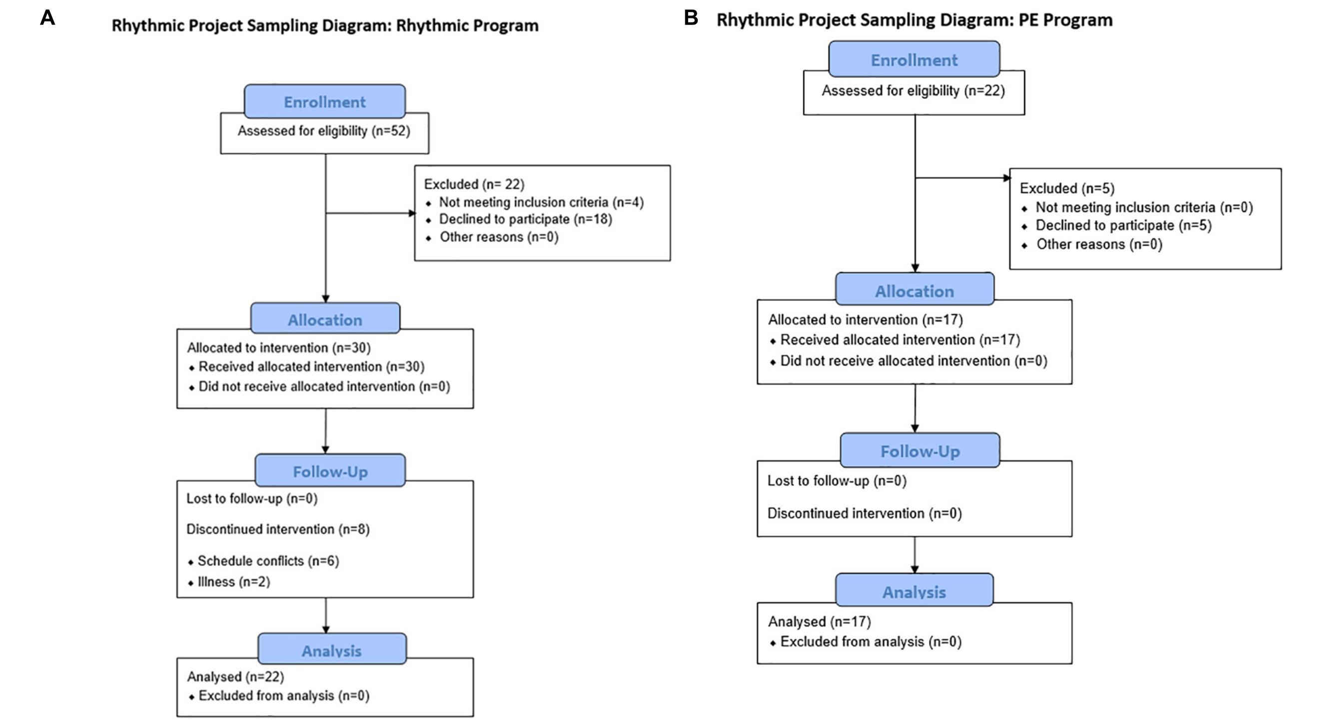

FIGURE 1 | Study flowchart showing retention of participants in the rhythmic **(A)** and the PE **(B)** group.

TABLE 1 | Demographic characteristics of participants in each program.

	Physical Education (*n* = 17)	Rhythmic (*n* = 22)
Sex	10 Male	11 Male
	7 Female	11 Female
Race/Ethnicity	15 Caucasian	15 Caucasian
	2 Asian	5 Asian
		1 African American
		1 Mixed
Average Age (years)	7.76 ± 1.64	7.64 ± 1.47
Average Height (cm)	134.33 ± 10.40	135.18 ± 10.95
Average Weight (kg)	31.34 ± 8.53	30.61 ± 8.28
Average BMI (kg/m^2)	17.12 ± 3.17	16.44 ± 2.58
IQ Standard Score	107.76 ± 16.98	111.73 ± 15.15
IQ Percentile	62.34 ± 30.62	71.49 ± 27.71
Fitness Score	16.31 ± 10.37	14.29 ± 9.37

middle one, facing in the same direction. This task demands inhibition of attention to the fish in the center plus flexible switching of mindset and attentional focus to the new rules. In the Mixed Flanker task (45 trials), administered last, either the blue or the pink fish may appear and the child must respond based on the correct rule. The stimulus presentation time was 2100 ms, and a practice block for each task preceded the actual test. For each task, both accuracy (percentage of correct answers) and reaction time (RT) were recorded.

Perceived competence toward exercise programs was assessed using the five items from the perceived competence subscale of the Intrinsic Motivation Inventory (McAuley et al., 1989), which has been previously used in elementary physical education and other youth program settings (Standage et al., 2005; Agans et al., 2019). An example item is "When it comes to playing physically active games, I think I am pretty good," and the response scale ranged from 1 ("strongly disagree") to 5 ("strongly agree"). The alpha coefficient of internal consistency in the present study was acceptable, for both pretest (α = 0.80) and posttest (α = 0.70).

Relatedness was assessed with the 6-item Relatedness to Others in Physical Activity Scale (Wilson and Bengoechea, 2010). Children responded to a number of items following a stem phrase ("In the exercise classes I participate in, I feel") such as "I am included by others." Each item was rated using a five-point response scale (1 = strongly disagree, 5 = strongly agree). Cronbach's alpha coefficients of internal consistency in the present study were acceptable, for both pretest (α = 0.71) and posttest (α = 0.90).

Measures Across Intervention

Physical activity level

Accelerometer data and ratings of perceived exertion (RPE) were used as means of quantifying the physical activity intensity during all rhythmic and physical education lessons. A triaxial accelerometer (ActiGraph GT3X+; ActiGraph, Pensacola, FL, United States) was worn on the right hip over the clothes with an adjustable belt to objectively measure the total time spent in moderate or vigorous PA. ActiGraph monitors were downloaded using ActiLife v 6.11.4 software (ActiGraph, Pensacola, FL, United States) and were converted to 1-s epoch csv output files for further analysis. The percentage of time spent in moderate or vigorous PA during each 30-min lesson was estimated per child. Perceived exertion was assessed upon completion of each lesson using the boy and girl versions of the stepping Children's OMNI RPE scale (Robertson et al., 2005), which ranges from 0 (not tired at all) to 10 (very, very tired).

Fidelity checklist

A fidelity checklist was developed to assess whether the PA programs were implemented as originally planned (**Table 2**). Specifically, the checklist assessed whether the rhythmic program provided opportunities for a variety of rhythmical gross motor actions with music, sounds, and manipulatives as well as social interactions. Similarly, the focus of the physical education lessons was assessed, which targeted working on all fundamental motor skills and fitness components, without specific emphasis on rhythmic movement.

Process evaluation measures

The pictorial Feeling Scale (FS; Hardy and Rejeski, 1989), as adapted for children by Hulley et al. (2008), was used to measure affective valence from the experience in the PA programs, completed at the end of each lesson. The Feeling Scale is an 11-point single-item bipolar scale, asking children "How do you feel right now?", with scores ranging from -5 ("Very bad") to +5 ("Very good") accompanied by gender-specific drawings ranging from a sad face (-5) to a happy face (+5).

Enjoyment from each lesson was measured by asking children how much they enjoyed the lesson with a 5-point single-item asking "How fun was the lesson today?" Children rated their enjoyment on a Likert scale, ranging from 1 (not at all fun) to 5 = very fun. This item was added in addition to the pictorial Feeling Scale to make it easier for the younger children to respond on how they felt about the lessons.

Cognitive engagement during each lesson was rated using a 5-point single-item asking, "How much did you use your brain to think during the lesson?" Children rated their cognitive engagement on a scale ranging from 1 (not at all) to 5 (very much) immediately upon completion of the lesson. The item was developed for the purposes of this study based on previous work on cognitively engaging PAs in youth (Schmidt et al., 2016).

Engagement during the lesson was observed by trained research assistants. The level of engagement was scored as the degree the children listened to and followed the program instructions throughout the 30-min lesson, with 1 indicating little engagement, 2 indicating moderate engagement, and 3 indicating strong engagement.

The motivational climate created by peers for the rhythmic program was measured with a modified version of the Peer Motivational Climate in Youth Sport Questionnaire (Ntoumanis and Vazou, 2005). The peer climate included 8 items from the task-involving motivational climate higher-order factor. Children responded to items assessing the degree to which their peers "helped each other improve," "said nice things when I tried," etc. In order to measure how supported children felt by the teacher, three additional items on teacher support (from the Learning Climate Questionnaire, Williams and Deci, 1996) were included in our research: "my teacher provided me with choices," "my teacher encouraged me to make my own moves in the program," and "my teacher understood me." Cronbach's alpha coefficients of internal consistency in the present study were acceptable, for both peer climate ($\alpha = 0.89$) and teacher support ($\alpha = 0.70$). The motivational climate and teacher support were administered at the end of the implementation period for the rhythmic group.

In addition to quantitative process evaluation data, five open-ended questions were developed to measure parent and child perceptions of the rhythmic program. The questions referred to the overall experience of children, what children liked or did not like as much, what the parents thought about the program, and any suggestions for changes if the program was offered in the future. The questionnaire was completed anonymously and placed in a sealed box available at the waiting area of the gymnasium.

Procedure

Before the 7-week implementation period, all children engaged in two pre-session visits at the researchers' university laboratory and gymnasium, lasting approximately 1 h each, for the collection of the consent forms, baseline, and pretesting assessments. Upon completion of the programs, a 1-h posttest evaluation was conducted. All testing was done individually, except for the PACER.

The intervention sessions for both the rhythmic and physical education groups took place in the gymnasium at the researcher's university and were scheduled at approximately the same time of day (between 2:00pm and 5:30pm). All children attended two 30-min sessions per week, for seven weeks. All lessons were delivered by the first two researchers with the assistance of trained undergraduate students. Upon entry into the gymnasium, each child was outfitted with an accelerometer and immediately upon completion of the lesson, participants completed the single-item measures (affective valence, exertion, cognitive engagement, enjoyment) individually, and the accelerometers

TABLE 2 | Fidelity checklist for physical activity programs.

	Rhythmic				Physical Education			
Focus	**Music**	**Sounds/ Singing**	**Mimic/Clapping/ Sticks**	**Partner work**	**Body Movement *(non-locomotor, locomotor)***	**Manipulative *(throw/catch, dribble, kick, volley)***	**Locomotor and Tumbling**	**Fitness *(obstacle courses)***
Percent	100%	71%	100%	78%	100%	57%	21.5%	21.5%

For the Rhythmic lessons, all 4 components were targeted per lesson. For the PE lessons, the focus was on one main category per lesson.

were removed. During each session, trained research assistants recorded observations for the fidelity assessment and of the students' engagement.

Rhythmic Program

For the rhythmic program, three separate time slots were offered to accommodate different schedules, with about eight participants in each session. Active learning of rhythmic gross motor actions in response to different songs was the primary activity. The rhythmic session began with rhythmic education in which participants learned to define a beat and identify the types of musical notes the beats hit (e.g., What is a beat? Eighth note, quarter note, half note, whole note?). Participants then learned to clap, jump, hop, walk, run, bounce a ball, and drum to the beat in different musical notes. After learning and practicing the basics, participants learned movement sequences set to steady, easy-to-follow, 4-count beats, with and without music. Each sequence emphasized moving precisely to the beat and incorporated full body movements and drumming. Participants were asked to count the beat of the music loudly while moving for better comprehension. The creative component of the lesson plans included moving freely to the beat of the music and creating new sequences to teach the other participants. The social component of the lesson plans included performing the movement sequences while facing each other, switching positions with each other during the sequence, creating new sequences with others, and learning new sequences from the other participants. A more advanced social rhythmic activity included tinikling, a Philippine inspired activity in which two participants adorned elastic strips to their ankles and jumped in tandem together twice and apart twice while other participants jumped in and out of the center of their strips without touching the strips.

Each session included progression in difficulty, with (a) warm-up activities involving moving across-the-room with different rhythmical locomotor skills and bouncing stability balls without music first and then with music, (b) movement patterns taught by the instructor, and (c) creative movement patterns developed by the participants alone or with a partner. Each rhythmic lesson plan tasked high cognitive load on working memory, attention, and executive functions. The rhythmic intervention utilized to a large extent the Drums Alive® program[1] that provides training as well as ready-to-use resources (activities, videos, and music) that are low cost and easy to use with relatively limited preparation time (preparation time always depends on the experience of the instructor; the more experience one gets, the less preparation time is needed). The main equipment utilized in the rhythmic program were stability balls, buckets as a base, and drumsticks (for the drumming activities), as well as poly-spots and stretch bands (for the jumping activities).

Physical Education

Two physical education sections were offered at the same time, with children grouped dependent on age. The PE classes were taught as a larger teaching opportunity for undergraduate students offered to homeschooled children in the community, with only a portion of enrolled students participating in the study. The physical education lessons are characterized as an active learning environment for gross motor actions, including developmentally appropriate activities on locomotor, non-locomotor, manipulative skills, and fitness. None of the physical education activities emphasized moving to the rhythm of music. The social component of the lesson plans included traveling to stations in small groups, playing team sports, and working together to complete a sequence of movements. Each physical education lesson tasked some cognitive load on working memory, attention, and EF.

Data Analysis

Data were analyzed using the Statistical Package for Social Sciences (IBM SPSS Statistics 26). The primary purpose of the study was to compare changes in motor and EF skills as a result of two treatments, namely, rhythmic exercise and physical education. Mixed-plot MANOVAs were conducted with two groups (intervention, comparison) for the between-subject factor and two time points (pre, post) for the within-subject factor, separately for each set of outcome variables. ANOVAs with a between-subject independent variable (group: rhythmic, physical education) were conducted for the process evaluation variables. Secondly, in order to examine associations between motor, hot and cool EF skills, and social–emotional characteristics of the program, three separate sets of correlations were conducted: (1) motor with hot EF and social–emotional factors; (2) motor with cool EF; and (3) hot EF and social–emotional factors with cool EF. For the correlations, the change scores for balance, Flanker tasks, and SWAN factors were calculated.

Scores on the Flanker tasks were filtered, and values were discarded according to the following criteria: (a) if they represented practice trials, (b) the first testing trial, (c) if RT < 250 ms, and (d) if they were outside 2 SD from the mean reaction time per task/per participant. Reaction time was quantified only for correct trials. Response accuracy was quantified as the proportion of correct responses relative to the number of trials administered. Repeated MANOVAs (group as the between-subject variable and time as the within) were conducted for the Standard, Reverse, and Mixed Flanker, with two dependent variables, namely, reaction time (in ms) and accuracy (%). Statistical significance was accepted at a level of $p < 0.05$. Effect sizes for differences between means were calculated using Cohen's *d*.

RESULTS

Intervention Fidelity and Feasibility of PA Programs (Rhythmic and PE)

Fidelity of Programs

The qualities of the rhythmic and the physical education programs are presented in **Table 2**. As shown in the Table, each of the rhythmic lessons focused on mimicking sounds with clapping or drumming sticks, listening to different beats of the music, and moving to the beat with locomotor (e.g., walking, jumping) or non-locomotor skills (e.g., bending, twisting). The

[1] www.drums-alive.com

majority of the lessons included working with a partner or a small group (78%) and singing or repeating sounds (71%; e.g., counting aloud) to the beat. For the physical education program, the focus of the majority (57%) of the lessons was on manipulative skills (e.g., passing, catching, dribbling, kicking, volleying), without excluding fitness lessons (obstacle courses and fitness stations), tumbling (e.g., rolling), and locomotor (e.g., dodging, galloping, jumping) skills.

Feasibility of Programs

The process evaluation data provide context about factors that may potentially influence implementation and outcomes. The descriptive statistics for the characteristics of the Rhythmic and PE programs are presented in **Table 3**. As evidenced, children in both groups had high attendance (>86%), with absences per child ranging from zero to four (Mean = 1.4, *SD* = 1.21). *T*-test comparisons showed no significant differences between groups for each of the process evaluation variables, except observed engagement. Specifically, data collected from each lesson showed that in both groups the children felt fairly good to good at the end of the lessons, perceived lessons as both fun and tiring, and believed they were cognitively engaged during the lessons. Further, there were no significant group differences in the MVPA levels during lessons or between students' perceptions of their competence and relatedness at the end of the implementation period. The only significant difference between groups was found on observed engagement, with the children in the PE group showing greater engagement during the lesson.

Rhythmic performance was measured before and after the implementation period to measure rhythmic skills, which were only taught in the rhythmic intervention program. Even though there was no significant difference between the two groups, the effect size for the rhythmic program was small-to-moderate (d = 0.42) whereas for the physical education program was null (d = 0.00). However, the large SD for the rhythmic group shows variability among children, suggesting that there may be substantial individual differences in this outcome or possible measurement error with the specific scale.

Qualitative Program Evaluation

Fourteen parents provided anonymous qualitative feedback reporting their impressions of the rhythmic program. All parents reported that their children liked the program and the activities, indicating that many children practiced them at home alone or with siblings. Some parents commented that their child's favorite parts of the intervention were working with a partner and having opportunities to be creative. Some students favored the drumming activities while others expressed that drumming was their least favorite activity. All parents reported that they really liked the program, and several parents expressed that they would not recommend any changes for the program. The suggestions for changes if the program was offered in the future were that it be provided more frequently or for a longer period of time, include more choices for students, and add instant activities for when children entered the gym to minimize waiting time (As this was a research study, instant activities were not offered in order to keep the duration of the lessons consistent for all participants).

Intervention Effects on Motor and Executive Function Skills

Independent sample *t*-tests revealed no baseline group differences across all outcome variables. Mean scores, standard deviations, and pretest–posttest effect sizes for all outcome variables are presented in **Table 4**.

Balance (MABC-2)

The 2 (group) by 2 (time points) ANOVA showed a significant main effect of time [$F(1,28) = 8.98$, $p = 0.006$, $\eta^2 = 0.24$] but no significant group or group by time interaction. Children in both groups improved their balance from before to after the 7-week period of implementation, with medium effect sizes for the PE group ($d = 0.58$) and small-to-medium effect sizes for the rhythmic group ($d = 0.35$).

Executive Functions (Flanker)

Repeated MANOVAs and the follow-up ANOVAs showed a significant main effect of time for the Standard [on RT: $F(1,37) = 53.24$, $p < 0.001$, $\eta^2 = 0.59$], the Reverse [on both reaction time and accuracy: $F(1,37) = 64.05$, $p < 0.001$, $\eta^2 = 0.63$; $F(1,37) = 13.89$, $p = 0.001$, $\eta^2 = 0.27$, respectively], and the Mixed Flanker [on both reaction time and accuracy: $F(1,37) = 15.14$, $p < 0.001$, $\eta^2 = 0.29$; $F(1,37) = 31.14$, $p < 0.001$, $\eta^2 = 0.46$; respectively]. No main effect of group or interaction effects were evident. In all Flanker tasks, both groups improved significantly over time with large effect sizes (**Table 4**). Specifically, on accuracy, the effect sizes were larger as the difficulty of the Flanker tasks increased for both groups, with the largest effect sizes observed on the Mixed Flanker (*d*'s = 0.97 and 0.85, for rhythmic and physical education, respectively). For reaction time, the effect sizes were large (*d*'s = 0.79 and 1.14, for rhythmic and physical education, respectively) on the Inhibitory control (Standard Flanker) and medium on the other tasks (*d*'s = 0.46–0.60) with the exception of the Reverse Flanker, where the largest effect size observed in the physical education group ($d = 1.43$).

Attention and Behavioral Control (SWAN)

Results from the mixed-plot ANOVAs showed no significant main or interactive effects on Attention and Behavioral Control. However, for the Rhythmic group the effect size was small and positive on Attention ($d = 0.19$) but null on Behavioral Control ($d = 0.04$), whereas for the physical education group the effect size was small and negative for both Attention and Behavioral Control ($d = -0.13$, $d = -0.35$, respectively).

Relationships Between Motor Skills, Hot and Cool EF, and Social–Emotional Factors

The results of the correlations between change scores for motor skills (e.g., balance), hot EF and social–emotional characteristics of the programs (SWAN ratings, affective valence, enjoyment, relatedness), and cool EF (Flanker accuracy scores and reaction time) are presented in **Table 5**. Between balance and cool EF, five of six correlations were in the hypothesized direction (positive), with two reaching

TABLE 3 | Descriptive statistics and baseline differences for the qualitative characteristics of physical activity programs.

Characteristics	Rhythmic		Physical Education		*t*-test (*p*-value)	Rating Scale/
	M	***SD***	***M***	***SD***		**Measure**
Attendance[≠]	86.36%	9.46%	92.86%	5.74%	–	Yes, No
MVPA[¥]	40.68	7.69	42.01	5.41	0.37 (0.548)	%
Perceived Exertion[¥]	4.00	2.20	3.08	2.20	1.68 (0.203)	0-10
Affective Valence[¥]	2.45	1.97	2.35	1.06	0.03 (0.859)	(−5) – (+ 5)
Enjoyment[¥]	3.65	0.95	3.81	0.63	0.34 (0.336)	1–5
Cognitive Engagement[¥]	3.78	0.10	3.48	0.77	1.11 (0.299)	1–5
Observed Engagement[¥]	2.51	0.44	2.98	0.06	**18.14 (0.000)**	1–3
Relatedness*	3.81	0.86	3.99	0.74	0.42 (520)	1–5
Perceived Competence*	4.02	0.62	4.21	0.46	1.003 (0.324)	1–5
Peer Climate*	3.74	0.76	–			1–5
Teacher Climate*	4.26	0.61	–			1–5
Rhythmic Performance[£]	6.24	17.06	0.00	3.24	1.16 (0.293)	1–64

*[≠]At the group level; [¥]Average scores from 14 lessons (7 weeks, twice per week); *Measured post implementation; [£]Measured at pre–post (change is provided). Values in bold show the significant results.*

TABLE 4 | Descriptive statistics (M, SD, ES) for motor, hot and cool executive functions.

	Rhythmic Program			Physical Education Program		
Task	**Pretest *M* (*SD*)**	**Posttest *M* (*SD*)**	**ES**	**Pretest *M* (*SD*)**	**Posttest *M* (*SD*)**	**ES**
Balance	25.72 (7.59)	28.33 (7.48)	0.35	24.92 (7.74)	29.25 (7.15)	0.58
Flanker—Accuracy						
Standard	83.16 (9.48)	85.83 (5.93)	0.34	83.05 (14.39)	87.55 (3.53)	0.43
Reverse	78.34 (11.82)	86.10 (7.38)	0.79	74.74 (17.62)	84.43 (5.86)	0.74
Mixed	67.88 (15.57)	81.42 (12.30)	0.97	69.41 (16.58)	80.52 (8.33)	0.85
Flanker—RT						
Standard	1246.09 (207.87)	1093.22 (175.45)	0.79	1325.41 (217.96)	1122.88 (126.89)	1.14
Reverse	1311.18 (269.34)	1155.91 (249.29)	0.60	1361.23 (179.45)	1112.12 (169.97)	1.43
Mixed	1372.23 (168.36)	1288.54 (134.43)	0.55	1358.82 (130.52)	1300.41 (124.08)	0.46
SWAN						
Attention	4.58 (0.63)	4.72 (0.80)	0.19	4.58 (0.52)	4.51 (0.52)	−0.13
Beh. Control	4.37 (0.94)	4.41 (0.93)	0.04	4.98 (0.93)	4.67 (0.85)	−0.35

TABLE 5 | Correlations among motor, hot and cool executive functions, and characteristics of the physical activity programs.

	Balance	Affect	Cognitive Engagement	Enjoyment	Exertion	Relatedness	Teacher Climate[≠]	Peer Climate[≠]	MVPA
Balance	–	−0.187	−0.116	−0.219	−0.233	0.017	−0.032	0.288	
Flk Stand AC	0.145	**0.366***	**0.540****	**0.460****	−0.276	0.201	0.221	0.179	0.105
Flk Rev AC	**0.443***	−0.042	0.005	0.226	0.101	0.085	0.102	0.298	0.043
Flk Mix AC	0.297	−0.115	−0.053	−0.083	0.104	−0.010	0.102	−0.107	−0.209
Flk Stand RT	0.293	−0.160	0.055	0.045	0.048	0.027	0.072	−0.064	0.045
Flk Rev RT	−0.016	−0.124	−0.071	−0.059	0.161	−0.112	−0.238	−0.439	−0.061
Flk Mix RT	**0.504****	0.054	0.037	−0.022	−0.099	−0.065	−0.120	−0.052	−0.109
Attention	−0.171	−0.014	0.139	0.027	−0.101	0.086	**0.491***	−0.167	0.195
Beh. Control	−0.265	−0.082	0.016	−0.110	−0.087	0.024	0.332	0.084	−0.086

N = 34. Change scores were calculated for Balance and Cognitive Function tasks. [≠]N = 17. Values in bold show the significant results.

statistical significance (e.g., balance with the Reverse Flanker accuracy and Mix Flanker reaction time). Balance was not correlated significantly with measures of hot EF (SWAN scores). Between change scores for measures of cool and hot EF, and social–emotional factors, significant positive correlations were found between the Reverse Flanker Accuracy score and children's self-rated Affective Valence, Enjoyment, and Cognitive Engagement during intervention sessions. No significant correlations were evident for Flanker tasks with Attention and Behavioral Control (SWAN scores). However, due to the small sample size these results should be interpreted with caution.

Exploratory Analyses: Social Context as an Important Contextual Factor

To gather preliminary data on potential social contextual factors that might impact outcomes in a PA intervention, we examined correlations between teacher climate, peer climate, and EF outcomes among the children in the Rhythmic group ($n = 17$). Teacher climate was positively correlated with Flanker accuracy scores, Attention, and Behavioral Control, and the correlation with Attention ($r = 0.491$) reached statistical significance. None of the correlations between peer climate and EF change scores were statistically significant. Again, given the small sample size, results should be interpreted with caution.

DISCUSSION

The aim of this pilot study was to examine the feasibility of a rhythmic PA program as well as the extent to which a 7-week rhythmic PA program, compared to a generalized physical education program, impacts motor and EF skills in children. Children in the rhythmic group participated in a novel PA program focused on rhythmic movement patterns with music and manipulatives over fourteen sessions (two 30-min sessions per week). As research on rhythmic PA programs is newly emerging, our focus was primarily on experiences derived from the implementation of a rhythmic PA program with a secondary focus on potential effects on motor and cognitive outcomes in order to generate hypotheses for a full-scale randomized intervention study.

Intervention Fidelity, Acceptability, and Feasibility

First, fidelity checklists demonstrated that teachers were able to deliver the content of both the rhythmic and physical education lessons as intended. Second, children's experiences within and perceptions of the rhythmic program were measured using a variety of methods throughout each session, as well as at the end of the implementation period with a parental open-ended questionnaire. As the feasibility assessment showed, children enjoyed participating in the rhythmic intervention, perceived it to be cognitively engaging and a little tiring physically, and perceived both their peers and the teacher to be supportive and task-involving.

The inclusion of music and rhythmic movement patterns within an environment characterized by positive social interactions and task-involving teacher and peer climates made this PA intervention unique. Ours is one of the first studies to examine the social context of a PA intervention and supports the need for future consideration of instructional and peer climates. It is well-established that peer interactions affect children's motivation and behavior in school (Wentzel and Ramani, 2016), as well as in youth PA contexts (Harwood et al., 2015). According to Self-Determination Theory (Deci and Ryan, 2000), relatedness is one of the three basic psychological needs, along with competence and autonomy, the satisfaction of which leads to intrinsic motivation and adaptive motivational outcomes, such as effort and commitment. Relatedness refers to a sense of feeling connected to others, supported, and valued by significant others (Deci and Ryan, 2000). Youth PA programs that support the need for relatedness, especially by peers, reflect higher levels of engagement, intrinsic motivation, enjoyment, and perceived competence (Ntoumanis et al., 2007; Hein and Jõesaar, 2015; Sparks et al., 2015). The role of peer relatedness on cognitive outcomes remains largely unexplored. Diamond and Ling (2015) predicted that successful interventions on EF skills are likely to be those that create feelings of belonging to a group with an important shared goal, whereas PA without cognitive challenge and lack of any social component appear not to improve EFs. Future PA intervention research should address peer and teacher climates to extend our understanding of how climate may impact both engagement in PA and outcomes.

The inclusion of music is a strategy commonly used to facilitate positive affective responses during exercise even when the intensity is vigorous (Deforche and De Bourdeaudhuij, 2015; Vazou et al., 2019a), and results from this study extend prior findings by illustrating children's enjoyment of physical activities performed to music. The qualitative data from parents were very encouraging, suggesting that the children had positive experiences in the program, especially from the partner work and the creative components of the tasks, features of the intervention that should be promoted more extensively in future rhythmic programs. Suggestions from parents emphasizing the continuation of the program with a higher dose and frequency were heartening as they demonstrated demand for and interest in this type of intervention. Moreover, the use of a commercial program (Drums-Alive) with already developed resources (music, lessons), relatively low-cost equipment, and limited preparation time further illustrate that the rhythmic program is practical and could be easily delivered by PE teachers or other trained educators.

Intervention Promotion of Skill Acquisition and Cognition

Importantly, our intervention was uniquely designed to focus on learning to listen and practice rhythmic movement, a skill that has not been examined systematically in the chronic PA intervention and cognition literature. Results showed that the 7-week rhythmic program improved children's rhythmic skills ($d = 0.42$) and had a positive and meaningful effect on balance ($d = 0.35$), accuracy and response time on the Flanker tasks (d's = 0.34–0.97), and parent-rated attention ($d = 0.19$). Similarly, Lakes et al. (2019) found that music and rhythmic movement, through the Creatively Able program, resulted in group-level reductions in Stereotyped and Compulsive behaviors for children with Autism Spectrum Disorder. The inclusion of music as an element of a PA intervention is further supported by research in typically developing elementary children showing that music education has a positive effect on EF skills and academic achievement (Jaschke et al., 2018). Thus, rhythmic programs, in addition to having a potential beneficial effect on motor and EF skills, also have the potential to benefit academic achievement and literacy skills, especially in early years of a child's development (Bhide et al., 2013; Linardakis et al., 2013; Nelson, 2016). It has been suggested that rhythm and language show common developmental elements (Patel, 2003) and share some of the same auditory mechanisms (Degé and Schwarzer, 2011) as well as neural and cognitive resources that are necessary for both reading acquisition and music/rhythm understanding (Tierney and Kraus, 2013). Identifying factors that could potentially mutually help EF and literacy skills is particularly important considering the high percentage (5–17%) of schoolchildren who do not become fluent readers, even with explicit instruction (Shaywitz, 1998). This research on music and education supports the hypothesis that music could be an important contextual factor to include in PA interventions in order to synergistically improve executive functions and academic outcomes.

A process evaluation designed to control for potential covariation of PA intensity and other qualitative characteristics across the two programs (rhythmic and physical education) indicated that the programs did not differ in measures of PA intensity or children's perceptions of the experiences. The only process variable that was significantly different between the rhythmic and the physical education groups was the level of observed engagement of the children during the lessons. While engagement was high in both groups (means across 14 lessons of 2.51 and 2.98 on a 3-point scale, for the rhythmic and physical education groups, respectively), it was significantly higher for the physical education group. This observation may be attributed to the lack of familiarity with the novel and possibly unusual rhythmic motor patterns that were practiced in the rhythmic program (e.g., drumming on stability balls, tinikling), whereas the physical education program included activities that the children were more familiar with, such as tag games, dribbling, kicking, and passing. The difference in students' observed engagement may also be explained by the difficulty level of the tasks expected to be learned during the novel rhythmic lessons. It is possible that motor learning in the rhythmic program was more difficult because the tasks and motor patterns were new to the children. Even though the lessons were intentionally developed to provide variability of practice and to challenge the rhythmic and coordinative movements in order to enhance cognitive engagement and avoid automaticity (Pesce et al., 2013b, 2019), rhythmic programs may require either a longer duration of practice for successful performance and learning or increased scaffolding, hypotheses that need to be tested in future studies.

Our data showed that children in both programs improved significantly from pre- to post-intervention on balance and hot/cool EF skills, with no differences in changes between the two programs (i.e., one was not better than the other). Specifically, all children improved on balance, with the effect sizes being small-to-medium and medium for the rhythmic and the PE programs, respectively. Similar to our study, the enriched physical education program by Pesce et al. (2019) that was centered on being cognitively engaging and providing variability of practice showed improvements in all motor coordination skills in children, including balance.

Moreover, children in both groups improved on measures of cool EF, including reaction time in all three computerized tasks of EF (Standard, Reverse, Mixed Flanker) and on accuracy for both the Reverse and Mixed Flanker tasks. Notably, for accuracy, as the difficulty level of the Flanker tasks increased (by focusing on more than one executive process), the effect sizes were larger for both groups (*d*'s = 0.97 and 0.85 on the Mixed Flanker, for the rhythmic and physical education, respectively). Similarly, large effect sizes were found on reaction time for the Standard Flanker (inhibitory control) for both groups as well as on the Reverse Flanker (inhibition and cognitive flexibility) for the physical education group (1.43).

The improvement on tasks requiring all three cool executive processes (inhibition, cognitive flexibility, and working memory) suggest that developmentally appropriate PA programs of moderate-to-vigorous intensity (40–42%) that include cognitive engagement and variability of practice on fundamental motor skills can target a broad set of EF skills in children. Previous studies with rich PA interventions have also demonstrated positive effects on EF skills (Lakes and Hoyt, 2004; Chang et al., 2013; Lakes et al., 2013; Pesce et al., 2013a; Crova et al., 2014; Schmidt et al., 2015). However, in some studies, the results were not entirely consistent across all EF skills, suggesting differential associations between specific aspects of the PA programs and specific executive processes. For example, Schmidt et al. (2015) found that changes in inhibition were similar for all experimental groups (team games, aerobic, or traditional physical education) regardless of the intensity of the programs or the level of cognitive engagement, and working memory improved similarly for team games and the aerobic program but not in the physical education group. In contrast, cognitive flexibility improved significantly more for the team games program compared to the other two programs.

In our study, both accuracy and reaction time on all three cool EFs improved for both groups, but the present data are limited in that it cannot answer whether the improvements were simply due to maturation or to the characteristics of the PA programs. However, our results are in line with the conclusions of a recent meta-analysis (Vazou et al., 2019b), in which when a PA intervention, regardless of its qualitative characteristics (i.e., aerobic, motor skill, cognitively engaging), was compared to traditional physical education, which is known to be beneficial for children, the effects on the cognitive outcomes were of similar magnitude, with the pooled effect sizes being close to zero, and the largest effects being observed when comparing an intervention to no treatment. Thus, our design choices—using physical education as a control or comparison intervention—reduced our expectations for detecting large effects. These findings support the overall benefits of high-quality physical education delivered within the context of a research study.

Associations Between Motor Skills, Hot and Cool EF, and Qualitative Characteristics of the Programs

In this study, the associations between balance (a measure of motor skill), cool EF and hot EF, and social–emotional factors were also examined. The results showed significant positive correlations between balance and measures of cool EF, specifically accuracy on the Reverse Flanker task (Inhibition and Cognitive Flexibility) and reaction time on the Mixed Flanker task (Inhibition, Working Memory, Cognitive Flexibility), but not with the Standard Flanker task that only involves inhibition. Gross motor skills have been found to significantly relate to specific EFs, such as visuospatial working memory and response inhibition (van der Fels et al., 2019). Balance was not correlated significantly with measures of hot EF and social–emotional factors.

These results are consistent with prior research examining relationships between cool and hot EF and motor skills, which have demonstrated positive relationships between EF and gross motor skills, but failed to find the same relationship when looking specifically at balance. In a school-wide sample of 207 children, Lakes (2013) found that observer ratings of gross motor control (e.g., coordination, athleticism) were significantly correlated with measures of cool EF (working memory and mental math tasks) as well as a measure of hot EF (teacher ratings of problem behavior); moreover, Lakes (2012) reported significant correlations between observer ratings of motor control and observer ratings of cognitive and emotional control when completing a challenge course. When the differentiating effects of specific motor skills on EF were examined, Pesce et al. (2019) found that ball skills, but not balance, had a mediating role on the effect of a cognitively engaging physical education intervention on inhibition. Additionally, in a cross-sectional study with young tennis athletes, it was demonstrated that a longer duration of game-based exercises was associated with better reaction time in inhibitory control, and coordination training was related to accuracy in working memory (Ishihara et al., 2017). In sum, there is evidence that gross motor skills are associated with cool and hot EF, and studies examining specific motor skills have demonstrated some differences in the relationships with selective EFs when specific motor skills are examined. In future research, it would be helpful to differentiate between specific motor skills and cool and hot EF to further our understanding of how these factors are related as well as how they might be impacted by PA interventions.

Positive significant correlations were also evident between cool EF (i.e., accuracy on Standard Flanker) and affective valence, cognitive engagement, and enjoyment of the PA programs. Deriving satisfaction from a PA program and experiencing positive affect has been proposed to be associated with higher levels of engagement and self-regulatory skills (Isen and Reeve, 2005; Diamond, 2015; Brand and Ekkekakis, 2018). It is noticeable that significant positive correlations were observed only between affective valence, cognitive engagement, and enjoyment (qualitative characteristics of the PA programs) with the Standard Flanker, which is the easiest task as it is only tapping attention and inhibitory control without requiring working memory and cognitive flexibility demands. It is possible that these qualitative characteristics may have a larger impact in changes of the "simpler" EFs and not in EF tasks involving greater complexity (including working memory). However, due to the preliminary nature of this study, this finding needs to be further explored in the future. Lastly, a supportive teacher motivational climate significantly correlated with attention, suggesting that instructors are likely another important contextual factor in a given intervention that deserves further consideration. Future PA intervention research should include measures of teacher climate in order to assess whether or not teacher climate may mediate intervention effects.

Limitations and Future Recommendations

As this was a pilot study, several limitations should be taken into consideration both in planning future research and in interpreting the present results. These results clearly need to be replicated with a larger sample, and with a randomized sample. The lack of an inactive control group (wait list or no intervention) limits interpretation of the results. In addition, due to limited resources and time in the comparison group (most children had a limited time availability due to other after-school activities that restricted the number of measures we could use), balance was the only measure of motor skills that was evaluated. A wider assessment of motor skills, including both gross and fine motor skills (manual dexterity, ball skills, and balance), should be examined in the future, as we noted earlier that relationships between EF and motors skills may differ.

In this pilot study, we anticipated small effects for the rhythmic program, which were not found to be significant. As both programs did not differ on any of their characteristics other than the focus on rhythmic movement, it is possible that the dose of the rhythmic program (fourteen 30-min sessions) was not enough to create a significant difference on the motor and EF outcomes we examined. Especially given the novelty of the tasks and the fact that children perceived the rhythmic intervention as more difficult, it may be that they need a longer period of time to learn the skills and, thereby, demonstrate positive effects. This hypothesis, while clearly in need of further examination, suggests that different types of PA programs (potentially those that vary in complexity) may have a different timeline for motor and cognitive learning outcomes to be evident, which is something that should be taken into consideration when exploring the exercise–cognition relationship. Additional research is also needed regarding the potential success of the rhythmic program with children of different ages, skill levels, and cognitive development.

Our study provides evidence for the feasibility of the rhythmic program as well as recommendations for future acceptability, adaptation, and implementation of the program. Further, our study provides additional evidence related to the beneficial role of qualitatively rich PA programs that stimulate children's motor and EF skills and supports the suitability of such programs in physical education, as highlighted by exercise and cognitive scientists (Pesce, 2012; Diamond, 2015; Schmidt et al., 2015; Pesce et al., 2019; Tomporowski and Pesce, 2019; Vazou et al., 2019b). Lastly, this study contributes to the literature by exploring the potential value of rhythmic programs as a vehicle in helping children develop motor and EF skills while deriving joy and positive social interactions from the program. Additional research is clearly warranted to better understand the effects of different types of PA programs, and particularly rhythmic programs, on motor, cold EF, and hot EF skills and social emotional factors.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Iowa State University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

SV and AS designed the study, led the program implementation, interpreted the findings, and drafted the manuscript. BK contributed in the methodology, data collection, implementation of the programs, data processing, and helped drafting the manuscript. SV conducted the analysis. KL contributed in the methodology, interpreted the findings, and helped draft the manuscript.

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Task-Specific and Latent Relationships Between Motor Skills and Executive Functions in Preschool Children

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There has been an increasing interest in the relationship between motor skills and executive functions (EFs) in young children over the years. However, no clear picture on the relationship between both domains has emerged from these studies. We have extended previous findings by conducting a comprehensive examination of task-specific and latent relationships between a range of motor skills and EFs in preschool children. The sample consisted of 198 3- to 5-year-old children (102 boys; 51.5%). Motor skills were assessed using the Movement Assessment Battery for Children Second Edition. EFs were assessed with the performance-based tasks 'Day/Night,' 'Hand Tapping,' 'Forward Corsi Block,' 'Forward Digit Recall,' and 'Conflict Task,' and a rating-based EF measure (i.e., the Behavior Rating Inventory of Executive Functioning - Preschool version). Task-specific relationships were examined using zero-order Pearson correlations. Latent factors of motor skills and EFs were examined using confirmatory factor analysis and exploratory structural equation modeling. Structural equation modeling (SEM) was used to examine latent relationships. The results of the Pearson correlation analyses showed statistically significant albeit weak correlations between specific motor and EF items ($r = 0.15$ to $r = 0.23$). SEM showed non-significant weak relationships between a general motor factor (as a unitary latent construct) on the one hand, and performance-based EFs and rating-based EFs (as latent EF components) on the other hand. In conclusion, this study suggested only weak relationships between motor skills and EFs in preschool children with no clear differences between their task-specific and latent relationships.

Keywords: motor skills, executive functioning, inhibition, working memory, cognitive flexibility, early childhood, factor structure

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INTRODUCTION

Motor skills undisputedly play an important role in peoples' overall functioning. This is especially true for young children as the attainment of motor skills provides children with new opportunities for learning about their physical and social environment, both regarding objects and other individuals (Wilson, 2002; Adolph and Joh, 2007; von Hofsten, 2009). This theoretical claim about a relationship between the motor and cognitive domains, more specifically the relationship between motor skills and executive functions (EFs) has attracted the attention of many early childhood researchers over the years. Thus far, research has not been able to elucidate a clear picture on the relationship between these two domains (Livesey et al., 2006; Michel et al., 2011; Lehmann et al., 2014; Houwen et al., 2017; Oberer et al., 2017; Alesi et al., 2019; Maurer and Roebers, 2019), as studies have used different and sometimes limited sets of only one or two motor skills and/or EFs. In addition, previous studies have examined the relationship between motor skills and EFs on exclusively one level (i.e., on an item-level or a construct-level), making it difficult to gain insight into the multi-level nature of the relationship. It is important to know whether and to what extent a relationship between motor skills and EFs exists on an item-level and/or on a construct-level as this information may have implications for the design of early interventions. More specifically, it provides information whether interventions should be focused on the domains in general or on specific motor skills and/or EFs. For example, if a relationship exists between a specific motor task (e.g., threading beads) and a specific inhibition task (e.g., a Stroop task) without relationships between other specific fine motor and inhibition tasks, then interventions should focus on specific tasks without the expectation of a generic effect on the performance of other motor and EF tasks. On the other hand, if a relationship is found between fine motor skills and inhibition on a more general level (i.e., on a construct-level), then interventions can focus on several fine motor and/or inhibition tasks with the expectation of more generic effects on the performance of other fine motor and inhibition tasks as well. Therefore, this study extends previous research by examining both task-specific and latent relationships in a range of motor skills and EFs in order to provide more insight into the multi-level nature of the relationship between motor skills and EFs in preschool children.

From a theoretical point of view, there are several explanations for a relationship between motor skills and EFs. The embodied cognition theory suggests that cognition, including EFs, is grounded in motor development (Foglia and Wilson, 2013). Motor development provides children new opportunities for actively exploring their physical and social environment through ongoing perception-action cycles, which supports cognitive development (von Hofsten, 2007). The acquisition of new cognitive capacities, in turn, allows for the acquisition of more varied and complex motor skills (Adolph and Hoch, 2019). In a similar vein, the concept of reciprocity and the theory of automaticity have been put forward as being useful in understanding the active and ongoing interaction of motor and EF development (Kim et al., 2018; McClelland and Cameron, 2019). Reciprocity occurs when skills develop and improve alongside each other (McClelland and Cameron, 2019). The theory of automaticity posits that the performance of motor and cognitive tasks compete for the same attentional resources. Performance of a new motor task requires strong allocation of cognitive-attentional resources; but with practice resulting in automaticity of behavior, fewer cognitive-attentional resources are needed for successful performance (Floyer-Lea and Matthews, 2004). Thus, if a certain skill is automated, more attentional resources are available for executing cognitive processes (Cameron et al., 2015). Correspondingly, EFs are assumed to no longer be involved in automated motor tasks, making the simultaneous performance of a second EF-demanding task easier (Floyer-Lea and Matthews, 2004). In light of these theories, the development of motor skills and EFs can be seen as multilevel, interactive, and bidirectional (McClelland and Cameron, 2019).

Empirical examination of the relationship between motor skills and EFs is hampered by conceptual challenges such as lack of clarity regarding the structure of motor skills and EFs (Magill and Anderson, 2017; Karr et al., 2018). With regard to motor skills, there is debate as to whether motor performance is based on task specificity or a general motor construct. The *Specificity of Motor Ability Hypothesis* states that motor skills are specific to a particular task and are relatively independent from each other (Magill and Anderson, 2017). In other words, improvement in one motor skill does not ensure improvement in other motor skills. This hypothesis is supported by empirical studies showing low correlations between individual motor skill items in children (Haga et al., 2008; Lorås and Sigmundsson, 2012; Stöckel and Hughes, 2016; Gísladóttir et al., 2019). For example, Haga et al. (2008) found mostly no or non-significantly weak correlations between items of the Movement Assessment Battery for Children in 4-year-old children. The specificity of motor skills is further supported by studies in children showing that practice and experience with one motor skill have limited beneficial effects for the development and learning of other motor skills (Revie and Larkin, 1993). In contrast, the *General Motor Ability Hypothesis* claims the existence of a unitary motor construct underlying a wide range of related motor skills. Hands et al. (2018) suggest that low correlations between motor items do not dismiss a unitary underlying motor construct. For example, studies that have used statistical procedures such as factor analysis have supported an underlying unitary motor construct in children (Ibrahim et al., 2011; Schulz et al., 2011; Okuda et al., 2019). Based on these hypotheses, the current study will focus on both task-specific as well as latent relationships between motor skills and EFs.

In this study, we will use the Movement Assessment Battery for Children Second Edition (MABC-2, Henderson et al., 2007) to assess motor skills, as this is a comprehensive and widely used instrument for assessing motor proficiency and identifying motor coordination difficulties in children (Blank et al., 2019). Some studies have been conducted with regard to reliability and validity of this instrument, and these studies have shown good-to-excellent test-retest reliability and acceptable-to-good internal consistency (Ellinoudis et al., 2011; Smits-Engelsman et al., 2011). In addition, the MABC-2 discriminates reliably between typically developing children and children having motor coordination difficulties (Ellinoudis et al., 2011). With regard to the original three-factor structure of the MABC-2, mixed findings have been shown. Whereas the original three-factor structure of the MABC-2 has been replicated in preschool children (Psotta and Brom, 2016), other studies were not able to replicate the original three-factor structure but found a one-factor structure instead (Schulz et al., 2011; Okuda et al., 2019). Based on the original structure of the MABC-2 and the outcomes of previous studies regarding its factor structure, the present study takes into account both a one-factor structure and the original three-factor structure of the MABC-2 in examining the latent relationship between motor skills and EFs in the current study (**Figure 1**).

There is currently no univocal scientific consensus on the definition of EFs, but they are often defined as a set of higher-order cognitive processes that contribute to effortful, purposeful, and problem-solving behavior, with inhibition, working memory, and cognitive flexibility as its core components (Diamond, 2013). The model from Diamond (2013) suggests that the core components are the basis for more complex EFs, such as reasoning, problem solving, and planning, which start to develop at school-age. Studies examining the structure of EFs in preschool children, more precisely the extent to which EF corresponds to a unitary construct or encompasses separable but related components, have shown mixed results (Karr et al., 2018). Several studies concluded EF to be a unitary construct in preschool children (Wiebe et al., 2008, 2011; Shing et al., 2010; Willoughby et al., 2010, 2012; Fuhs and Day, 2011; Masten et al., 2012), while other studies focusing on preschool children identified a two-factor structure with inhibition and working memory/cognitive flexibility as latent components (Miller et al., 2012; Lerner and Lonigan, 2014; Usai et al., 2014; Monette et al., 2015) or a three-factor structure with inhibition, working memory, and cognitive flexibility as latent components (Hughes, 1998; Monette et al., 2011). It should be noted that cognitive flexibility tasks were not always included in the studies that examined the structure of EFs. Studies focusing on preschool children might have excluded it, because it is argued that cognitive flexibility emerges later in development (Müller and Kerns, 2015). There is thus no uniformity in the previous studies about the EF factor structure.

In order to provide a comprehensive examination of children's EFs, it has been suggested to include both performance-based and

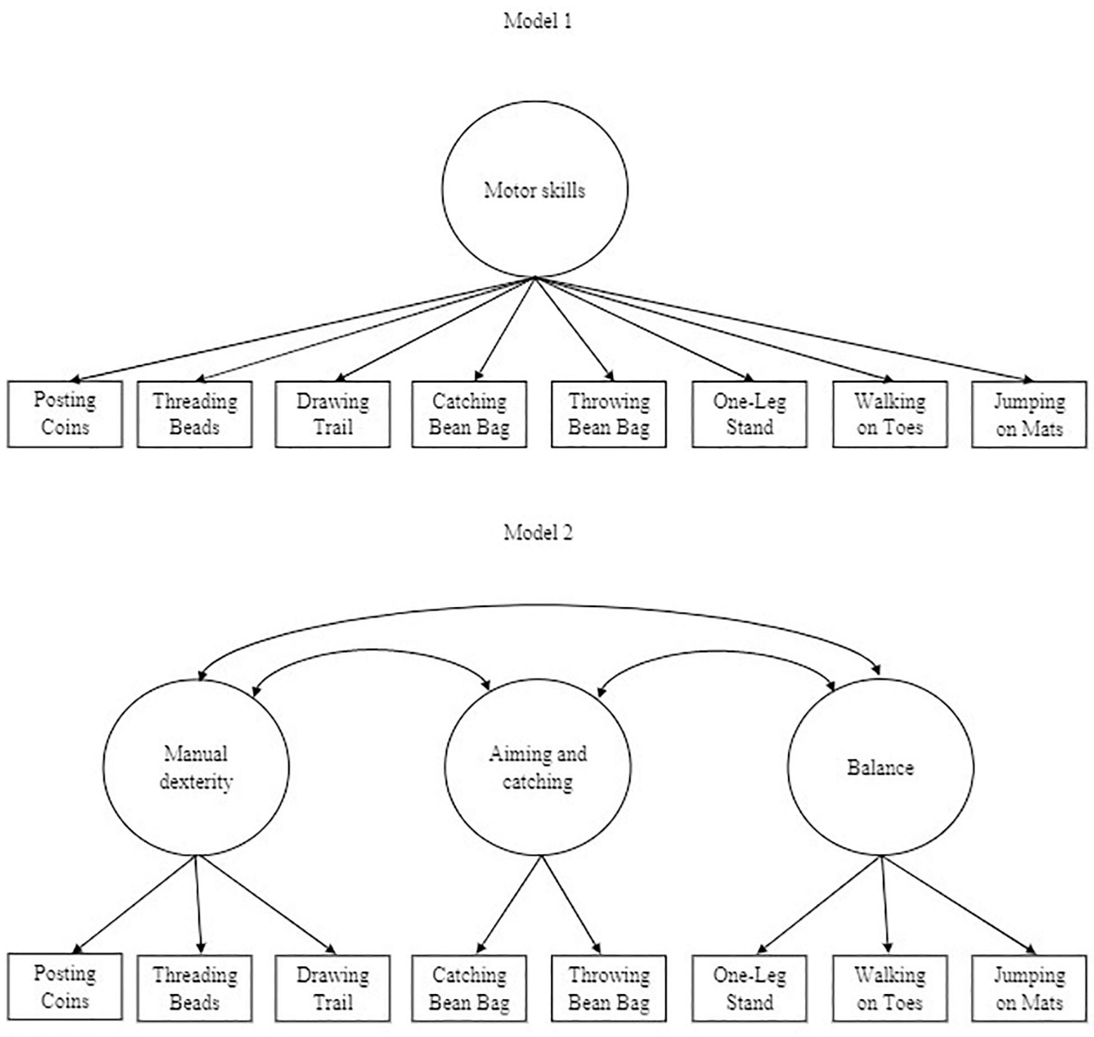

FIGURE 1 | One-factor model of motor skills. Model 1 illustrates latent motor skills as a one-factor structure. Model 2 depicts latent motor skills as a three-factor structure, based on the structure of the Movement Assessment Battery for Children Second Edition (Henderson et al., 2007).

rating-based measures (Toplak et al., 2013). Some researchers have suggested that performance-based and rating-based measures assess different aspects of EFs in school-aged children (Toplak et al., 2013), but empirical studies using both types of measures in preschool children have shown significant moderate correlations next to non-significant correlations (Loe et al., 2015; Miranda et al., 2015; Garon et al., 2016). Thus, research up until the present indicates that the extent to which performance-based and rating-based EF measures assess different or similar aspects of EFs in this age range remains unclear. Based on the findings regarding the relationship between performance-based and rating-based EF measures and the different structures of EFs in preschool children, the current study takes three different EF factor structures into account in examining the latent relationship between motor skills and EFs, as displayed in **Figure 2**: (1) a one-factor structure with performance-based and rating-based EFs, (2) a three-factor structure where inhibition, working memory, and cognitive flexibility were treated as separate latent constructs, and (3) a two-factor structure where performance-based EFs and rating-based EFs were treated as separate latent constructs.

In reviewing the empirical literature on the relationship between motor skills and EFs in preschool children, it has become clear that findings across studies are difficult to compare because of substantial disparities in methodologies. First, previous studies on the relationship between motor skills and EFs in preschool children have mainly focused on a limited set of motor skills and EF domains. For example, some studies have linked only fine motor skills to the three core components of EF (Michel et al., 2011; Roebers et al., 2014; Fang et al., 2017), while other studies have linked only gross motor skills to one or multiple EF domains (Heibel-Witte, 2016; Cook et al., 2019). These studies have shown inconsistent results regarding the relationship between motor and EF domains. For example, Fang et al. (2017) found significant weak relationships between fine motor skills, and inhibition and cognitive flexibility in children aged 4 to 6 years, but not between fine motor skills and working memory. Contrary to the results of Fang et al. (2017), Michel et al. (2011) found no significant relationships between fine motor skills and inhibition, working memory, and cognitive flexibility in typically developing children aged 5 to 7 years and a significant moderate relationship between fine motor skills and working memory in 5- to 7-year-old children with motor coordination difficulties, but not between fine motor skills, and inhibition and cognitive flexibility. Previous studies that used multiple tasks for measuring an EF domain have also reported inconsistent results between motor skills on the one hand and the tasks targeting the same EF domain on the other hand (Livesey et al., 2006; Lehmann et al., 2014). For example, Livesey et al. (2006) examined the relationship between motor skills and different inhibition tasks in 5- to 6-year-old children. Significant moderate-to-strong relationships were found the motor component scores of the MABC-2 and the 'Day/Night,' while non-significant relationships were found between the motor component scores of the MABC-2 and the Stop-Signal task. The inconsistent results suggest that the relationship between motor skills and EFs in preschool children is task-specific and emphasize the need for a comprehensive examination of their relationship.

This task-specificity of the relationship between motor skills and EFs has been suggested in previous studies (Roebers and Kauer, 2009; Michel et al., 2011; Stöckel and Hughes, 2016). If the relationship between motor skills and EFs is task-specific, it can be expected that interventions targeting specific motor skills also influence specific EFs, yet not all EFs. Inversely, because of the bidirectional relationship between motor skills and EFs (e.g., Roebers et al., 2014), interventions targeting specific EFs are expected to also influence specific motor skills, yet not all motor skills. Based on this assumption, interventions should focus on specific motor skills and EFs, and professionals should choose interventions carefully by selecting interventions that target the specific skills of interest. Therefore, the inclusion of a comprehensive variety of motor skills and EFs is important in providing a more comprehensive view of how motor skills and EFs are related during the preschool period.

Another methodological disparity is that previous studies in preschool children have examined the relationship between motor skills and EFs on exclusively one level (i.e., on an item-level or on a construct-level). Most studies have linked specific component scores of a motor test (on a construct-level) to specific EF task scores (on an item-level) (e.g., Livesey et al., 2006; Michel et al., 2011; Lehmann et al., 2014; Alesi et al., 2019). These studies showed widely varying relationships, even within a specific study, from non-significant to significantly strong. Three other studies examined latent relationships between motor skills and EFs by linking latent components of motor skills (in these cases: fine motor and/or gross motor skills) to a unitary latent factor of EF (Roebers et al., 2014; Oberer et al., 2017; Maurer and Roebers, 2019). These studies found moderate-to-strong relationships. Furthermore, some studies examined task-specific relationships between motor skills and EFs and reported relationships varying from moderate to none; however, most of the relationships found were weak relationships (Roebers et al., 2014; Fang et al., 2017; Oberer et al., 2017; Maurer and Roebers, 2019). In conclusion, there seems to be no clear pattern in the findings from the use of specific items, latent constructs, or a combination of the two. In order to get more insight into the multi-level nature of the relationship between motor skills and EFs, it is important to examine both task-specific and latent relationships in one study. Such a comprehensive examination will provide more fine-grained information on what and how components of motor skills and EFs are related.

In summary, the multi-level nature of the relationship between motor skills and EFs in preschool children is still not well-understood and further research is warranted. Therefore, the aim of the current study was to get a more fine-grained understanding of the multi-level nature of the relationship between motor skills and EFs in preschool children by examining their task-specific and latent relationships, including a range of motor skills (i.e., manual dexterity, aiming and catching, and balance skills) and EFs (i.e., performance-based and rating-based inhibition, working memory, and cognitive flexibility). This study took an exploratory approach with regard to the relationship between motor skills and EFs, because of 1) the mixed findings of

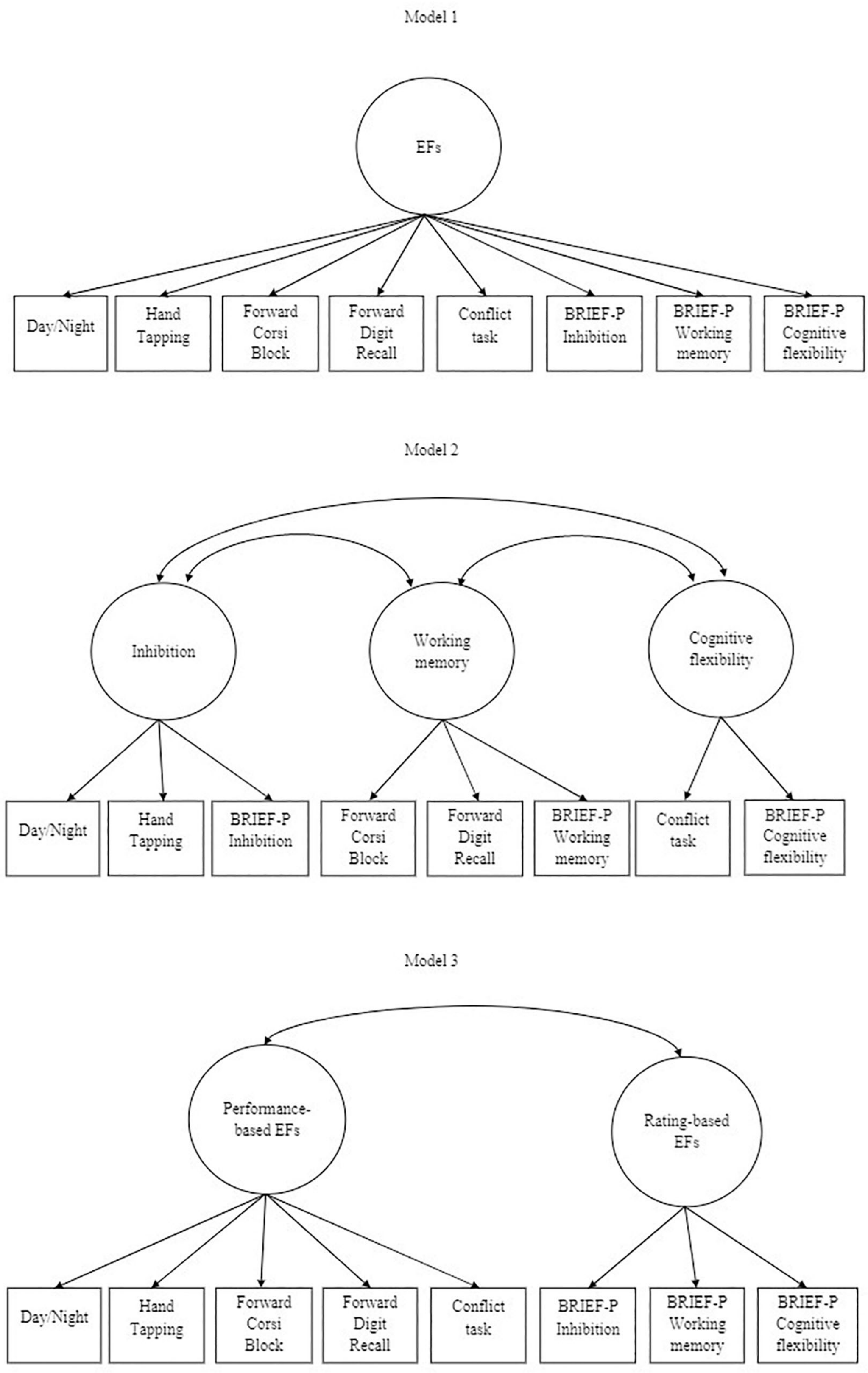

FIGURE 2 | Factor models of EFs. Model 1 illustrates latent EFs as a one-factor structure. Model 2 depicts latent EFs as a three-factor structure. Model 3 illustrates latent EFs as a two-factor structure.

empirical studies focusing on the relationship between motor skills and EFs in preschool children and 2) the absence of studies examining both task-specific and latent relationships between motor skills and EFs.

MATERIALS AND METHODS

Participants

The current study sample was part of a larger research project 'MELLE' (Motor skills, Executive functions, Language, and LEarning outcomes in preschool children; see also Houwen et al., 2019) in which 3- to 5-year old children are followed regarding their motor skills, EFs, and language abilities. From April 2016 to October 2019 a sample of 207 typically developing children was recruited from kindergartens, preschools, primary schools, and day-care centers, and via social media, flyers and posters distributed at supermarkets, stores, and playgrounds. Inclusion criteria were: (a) age between 36 and 72 months, (b) no signs of a medical condition (e.g., heart disease), neurological disorder (e.g., cerebral palsy), or intellectual or physical disability (e.g., club foot), (c) normal hearing and normal or corrected to normal vision, (d) being able to follow the test instructions, and (e) having parents/caretakers who have sufficient proficiency in written Dutch to be able to complete the questionnaires.

Nine children (4.4%) were removed from the original sample because of more than 50 percent missing values due to refusal, lack of concentration, or motivation. All of these nine children were 3- or 4-year old children with the majority being 4 years of age (n = 6; 66.7%). Most of these excluded children were girls (n = 6; 66.7%). Therefore, the final sample consisted of 198 children (102 boys; 51.5%), aged 36 to 71 months old (M = 50.9 months, SD = 10.1 months). The sample consisted of 83 3-year olds (42 boys; 50.6%), 63 4-year olds (36 boys; 57.1%), and 52 5-year olds (24 boys; 46.2%).

Instruments

Motor Skills

Motor skills were assessed with age band 1 of the Movement Assessment Battery for Children Second Edition – Dutch version (MABC-2; Henderson et al., 2010). It consists of eight tasks divided over three subscales: (1) manual dexterity, which consists of the items 'Posting Coins,' 'Threading Beads,' and 'Drawing Trail,' (2) aiming and catching, which includes the items 'Catching a Bean Bag' and 'Throwing a Bean Bag,' and (3) balance, which consists of the items 'One-Leg Stand,' 'Walking on Toes,' and 'Jumping on Mats.' Raw items scores were transformed to age-based item standard scores (range = 1–19, M = 10, SD = 3). Age band 1 of the MABC-2 has been found to be a reliable and valid measure to assess motor skills in preschool children (Ellinoudis et al., 2011; Smits-Engelsman et al., 2011; Psotta and Brom, 2016).

Performance-Based EFs

Five performance-based EF measures were used for inhibition, two for working memory, and one for cognitive flexibility. The EF tasks were age adequate and required either a motor or verbal response. The raw task scores of all performance-based EF measures were converted into z-scores per age group.

Inhibition

The 'Day/Night' (Gerstadt et al., 1994) is a verbal inhibition task. Children were shown black cards with a moon and stars and white cards with a sun. They were requested to say "day" to the moon card and "night" to the sun card. The task started with two practice cards followed by 16 test cards. The test cards were presented in the following order: moon card (m), sun card (s), s, m, s, m, m, s, s, m, s, m, m, s, m, s. Similar terms for day and night were scored as correct (e.g., "light" or "sun" instead of day). The amount of correct responses was scored (0-16). Studies have shown good internal consistency (Chasiotis et al., 2006; Rhoades et al., 2009) and test-retest reliability (Thorell and Wåhlstedt, 2006) in preschool children.

The 'Hand Tapping' (Diamond and Taylor, 1996) is a fine motor inhibition task. Children were asked to tap once when the tester tapped twice and to tap twice when the tester tapped once. The task consisted of two practice trials and 16 test trials. The series of the tester's tap was as follows: 1, 2, 2, 1, 2, 2, 1, 1, 1, 2, 1, 2, 2, 1, 1, 2. The number of correct responses (0-16) was scored. Studies have reported good internal consistency (Blair and Razza, 2007; Bierman et al., 2008; Rhoades et al., 2009).

Working Memory

The 'Forward Corsi Block' (Pickering et al., 1998) is a visuo-spatial working memory task. Children were asked to reproduce the same sequence of blocks tapped by the tester. Number sequences increased from two to six blocks, with three trials per sequence length. The test was terminated after three incorrect responses within one sequence length. The total score was the number of correct responses (0-15). The 'Forward Corsi Block' showed good test-retest reliability in preschool children (Alloway et al., 2006, 2009).

The 'Forward Digit Recall' (Gathercole and Pickering, 2000) is a verbal working memory task. Children were requested to recall the numbers said by the tester in the same order. Number sequences increased from two to seven digits, with three trials per sequence length. The test was terminated after three incorrect responses within one sequence. The total score was the number of correct responses (0-18). The test-retest reliability of the 'Forward Digit Recall' has been reported to be acceptable to good in preschool children (Alloway et al., 2006; Müller et al., 2012).

Cognitive Flexibility

We used a modified version of the 'Conflict Task' (Beck et al., 2011) for measuring cognitive flexibility using fine motor demands, which is adapted from the standard Dimensional Change Card Sorting task (Zelazo, 2006). The children were presented with two recipe boxes with slots cut in the top. A yellow target card with an airplane was attached to the front of one box. A red target card with a truck was attached to the front of the other box. The task consisted of two levels. In the first level, children were presented yellow cards with trucks and red cards with airplanes. They were asked to sort the cards according to the shape for six trials and then to sort the cards according to the color for six trials. In the second level, some of the cards contained a black border around the card and some did not. Children were asked to sort by color if the card had a black border around it and by shape if the card did not have a black border around it. This level consisted of a practice phase, in which the children practiced four cards, two with borders and two without. In line with Beck et al. (2011), the children were presented six cards with a border (B) and six cards without a border (NB) in the following order: B, NB, B, B, NB, NB, B, B, NB, NB, B, NB. The total score was the number of correct responses of both levels (0-18). Both levels of the 'Conflict Task' have shown good test-retest reliability (Beck et al., 2011).

Rating-Based EFs

The Dutch version of the Behavior Rating Inventory of Executive Function – Preschool version (BRIEF-P; Van der Heijden et al., 2013) is a standardized questionnaire consisting of 63 items that measure everyday EF in the home environment of children aged 35 to 71 months old. Parents were requested to rate how often their child exhibited various behaviors related to EF in the past 6 months on a three-point scale (1 = never, 2 = sometimes, 3 = often). Corresponding to the performance-based EF component measures, only the subscales Inhibition (16 items; e.g., "Is impulsive"), Working Memory (17 items; e.g., "Has trouble finishing tasks"), and Cognitive Flexibility (10 items; e.g., "Is upset by change in plans and routines") were included in the current study. Age- and gender-corrected T-scores ($M = 50$, $SD = 10$) were calculated for the three subscales in which higher scores are indicative of poorer EF. The T-scores were reversed in order to keep the interpretation of all tests in the same direction, namely higher scores reflecting better EFs. The Dutch version of the BRIEF–P showed sufficient to high internal consistency, test–retest reliability, interrater reliability, and construct validity (Van der Heijden et al., 2013).

Procedure

The study protocol was approved by the Ethics Review Committee of the Department of Pedagogical and Educational Sciences, Faculty of Behavioural and Social Sciences, University of Groningen. All parents gave written informed consent in accordance with the Declaration of Helsinki. The data were collected by graduate students in Pedagogical and Educational Sciences, Psychology, and Human Movement Sciences. Before they were allowed to collect any data, they had to follow and pass an extensive training. As part of the training, they read test manuals and followed two training sessions in which they practiced administering the tests on each other. Furthermore, they performed two video-taped practice assessments with a preschool child on which they were provided individual feedback.

Data collection consisted of two home sessions, each lasting 90 to 120 minutes, in which the children performed several motor, cognitive, and language tests as part of the MELLE study. The assessments were videotaped for scoring purposes, and to allow for later review of the data and fidelity in following testing procedures. Children were encouraged with stickers after every task. When necessary, breaks were used to maintain attention and motivation. After each assessment, children received a small gift and a diploma. Parents filled out questionnaires on their child's development, behavior, and daily environment. Parents received a report with the test results of their child. To ensure confidentiality, data were entered and stored using a personalized study identifier.

Analysis

Missing value analysis was conducted using SPSS Version 25 (IBM Corporation, 2017). Little's MCAR test was used to evaluate the missing at random pattern of missing values. Assumptions of normality, linearity, and homoscedasticity were examined with boxplots, histograms, and scatterplots. The BRIEF-P subscale scores were transformed by multiplying the scores with -1 in order to be consistent with the motor and EF task scores (where higher scores reflect better functioning). Relationships between specific items of motor skills and EFs were examined with zero-order Pearson correlation analysis.

In order to be able to merge the data of 3-, 4-, and 5-year olds, we tested the invariance of the correlation matrices separately for the motor and the EF scores across age groups by means of multi-group invariance testing in LISREL 8.8 (Jöreskog and Sörbom, 2006). As a main indication of model fit, the ratio of χ^2 to the degrees of freedom (χ^2/df) was used. In contrast to χ^2 or the p-statistic, the χ^2/df-measure is less sensitive to group sizes and departures from normality (Marsh and Hocevar, 1985; Byrne, 1989). According to Byrne (1989), a χ^2/df-ratio equal to or below 2 can be considered a good fit. The comparative fit index (CFI) (Bentler, 1990) was also examined as an additional indication of model fit. This index also reflects the model fit relatively well at all sample sizes. All further analyses were performed in MPlus Version 8.3 (Muthén and Muthén, 2019).

To test the fit between the latent structure of motor skills and EFs in 3- to 5-year-old children, we started with performing confirmatory factor analysis (CFA) as this analysis is the most parsimonious (Marsh et al., 2014). Modification indices were analyzed to examine whether and how the model fit could be improved with the addition of co-variances. Hence, from a two-factor model onward, we performed exploratory structural equation modeling (ESEM) in addition to CFA, because this analysis is less restrictive to fit the observed data than CFA and it allows cross-loadings between factors (Marsh et al., 2014). An example of an ESEM is shown in **Figure 3**. As suggested by Marsh et al. (2013), the ESEM factor structure was used in further analysis when the ESEM results fitted the data better than the corresponding CFA model results, with the absence of inflated fit indices. Otherwise, the CFA factor structure was used, on the basis of parsimony. Regarding ESEM, Geomin, an oblique rotation method, was used to establish the optimum pattern of item loadings. The factor structures that were tested for motor skills were (1) a one-factor structure, and (2) a three-factor structure consisting of fine motor skills, ball skills, and balance. The factor structures that were tested for EF were (1) a one-factor structure with performance-based and rating-based EFs, (2) a three-factor structure where inhibition, working memory, and cognitive flexibility were treated as separate latent constructs, and (3) a

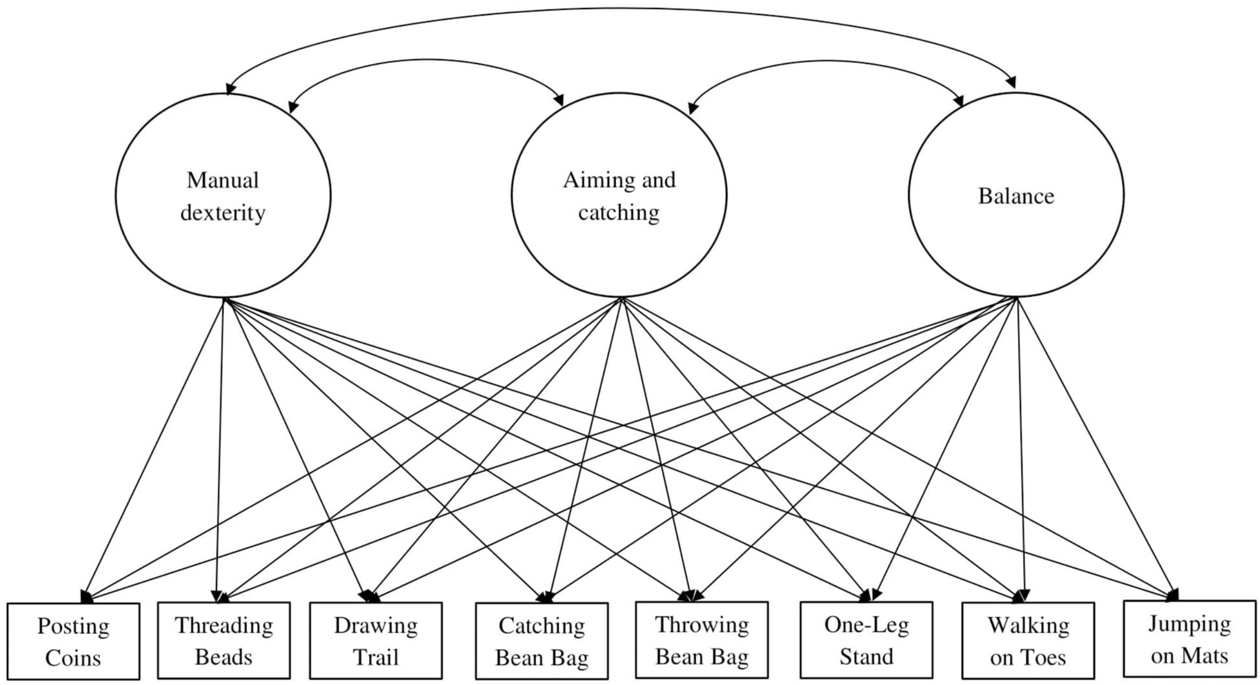

FIGURE 3 | Exploratory structural equation model of the three-factor model of motor skills.

two-factor structure where performance-based EFs and rating-based EFs were treated as separate latent constructs. The model fit was evaluated using several model fit measures. Criteria for good model fit were low values of χ^2 (with a corresponding non-significant *p*-value, indicative of a non-significant discrepancy between the data and the imposed factor structure), Root Mean Square Error of Approximation (RMSEA) and Standardized Root Mean Square Residual (SRMSR) < 0.08, and CFI and Tucker-Lewis Fit Index (TLI) > 0.90. It should be noted that, although these are the best model fit measures available for ESEM, there is incomplete evidence to confirm that these model fit measures are suitable to be used in ESEM studies (Marsh et al., 2009).

Next, the motor model and EF model that showed a good fit to the data were related to each other using SEM in order to evaluate relationships between latent variables of motor skills and EF. To evaluate the goodness-of-fit of the structural equation model, χ^2, RMSEA, CFI, TLI, and SRMSR were used.

RESULTS

Preliminary Analyses

Descriptive statistics are provided in **Table 1**. The rate of missingness varied from 0% (age and gender) to 22.2% ('Day/Night') (see **Table 1** for the amount of available data per variable). Little's MCAR test indicated the missing values (6.6%) were not missing completely at random (Little's MCAR test: χ^2 (626) = 719.719, $p = 0.005$). Taking a more detailed look at the missing values, the pattern of missingness appeared to be dependent on age and gender. Three-year-old children had more missing values than four- and five-year-old children. Additionally, boys had more missing values than girls. The missingness appeared to be related to observed variables (i.e., age and gender), which supports the use of multiple imputation under missing at random conditions (Graham, 2009). Analyses

TABLE 1 | Descriptive statistics for original motor and EF scores.

	Original			
	n	***M***	***SD***	***Range***
Posting Coins	193	10.57	2.46	2–14
Treading Beads	194	10.13	2.53	1–16
Drawing Trail	197	9.25	2.49	1–15
Catching a Bean Bag	194	9.41	2.90	1–16
Throwing a Bean Bag	197	10.16	3.13	2–19
One-leg Stand	190	8.38	2.34	3–17
Walking on Toes	186	9.61	3.07	2–15
Jumping on Mats	195	9.53	3.14	1–12
BRIEF-P Inhibition	193	−50.80	10.09	−88– −34
BRIEF-P Working Memory	193	−51.55	10.22	−84– −36
BRIEF-P Cognitive Flexibility	193	−51.66	10.74	−82– −37
Day/Night	154	0.00	0.99	−3.84–1.45
Hand Tapping	156	0.00	0.99	−4.85–1.50
Forward Corsi Block	159	0.00	0.99	−2.57–3.54
Forward Digit Recall	166	0.00	0.99	−2.37–3.11
Conflict task	174	0.00	0.99	−3.05–1.87

BRIEF-P: Behavior Rating Inventory of Executive Functioning - Preschool version.

of scatterplots and boxplots showed neither significant outliers, nor violations of linearity and homoscedasticity assumptions. Histograms revealed small deviations from normality for the 'Drawing Trail,' 'Jumping on Mats,' 'Day/Night,' 'Hand Tapping,' and the BRIEF-P subscales.

The multi-group invariance assumption of the correlation matrices across the 3-, 4-, and 5-year olds on the eight motor items was not rejected by the data (χ^2 = 51.25, *df* = 72, χ^2/df = 0.71, *p* = 0.97, *p*-value for test of close fit, RMSEA = 0.99, CFI = 1.00). In addition, inspection of modification indices also did not reject the multi-group invariance assumption. The multi-group assumption of invariance of the correlation matrices across the 3-, 4- and 5-year olds on the eight EF items was not rejected by the data (χ^2 = 50.05, *df* = 72, χ^2/df = 0.69, *p* = 0.98, *p*-value for test of close fit, RMSEA = 0.99, CFI = 1.00). Inspection of the modification indices did not point to violations of the invariance either. Hence, the aggregation of the correlational motor skills and EF data across age groups is highly defendable.

TABLE 2 | Bivariate correlations between specific motor and EF items.

	BRINH	BRWM	BRCF	DN	HT	Corsi	DR	Conflict task
MD1	0.00	0.03	0.05	0.02	0.22**	0.08	0.07	0.09
MD2	0.03	0.07	0.04	0.06	0.16*	0.08	0.00	0.13
MD3	−0.01	0.02	−0.10	0.12	0.15*	0.23**	0.09	0.12
AC4	0.13	0.03	0.09	0.02	−0.01	0.05	−0.05	0.08
AC5	0.03	−0.03	−0.05	−0.02	−0.10	−0.07	−0.04	−0.07
BA6	0.11	0.13	0.12	0.04	0.06	0.14	0.05	0.02
BA7	0.00	−0.01	0.08	0.11	0.03	0.01	0.08	0.15
BA8	0.13	0.09	0.04	0.06	0.02	0.17*	−0.11	0.05

**p < 0.05; **p < 0.01 (two-tailed). MD1: Posting Coins; MD2: Threading Beads; MD3: Drawing Trail; AC4: Catching a Bean Bag; AC5: Throwing a Bean Bag; BA6: One-leg Stand; BA7: Walking on Toes; BA8: Jumping on Mats; BRINH: Behavior Rating Inventory of Executive Function Preschool Version (BRIEF-P) Inhibition subscale; BRWM: BRIEF-P Working Memory subscale; BRCF: BRIEF-P Cognitive Flexibility subscale; DN: Day/Night; HT: Hand Tapping; Corsi: Forward Corsi Block; DR: Forward Digit Recall.*

Relationship Between Specific Motor and EF Items

To account for potential bias resulting from missing data and to increase statistical power in correlation analysis, multiple imputation with full conditional specification was performed in SPSS 25 (IBM Corporation, 2017). Age and gender were used as predictors and the motor skill and EF variables were used as predictors and variables to be imputed. Twenty multiple imputed data sets were created, as this amount of imputed data sets leads to a preventable power fall off of less than 1% (Graham et al., 2007). Cohen's *d* analysis demonstrated that the original and pooled means of the motor and EF scores were similar for the whole sample (*d* = 0.00 to *d* = 0.07; Cohen, 1988). Pearson correlation analysis was performed on each imputed data set individually and the results were pooled by making use of SPSS tabular output by default.

Data for some variables were not normally distributed; however, with a sample size of 198, the central limit theorem suggests that parametric tests (Pearson correlation) would still be sufficiently robust to avoid deviations from normality. **Table 2** provides an overview of the zero-order correlations between the specific motor and EF items. Statistically significant, albeit weak, positive correlations (*r* = 0.15 to *r* = 0.22) were found between all manual dexterity tasks and 'Hand Tapping.' Furthermore, the 'Drawing Trail' and 'Jumping on Mats' task correlated significantly, but weakly, positively with the 'Forward Corsi Block' (*r* = 0.17 to *r* = 0.23). There were no significant correlations between the motor tasks and the BRIEF-P subscales.

Factor Structure of Motor Skills

Because of the complexity of the analyses in MPlus, we accounted for deviations from normality in combination with missing values using robust maximum likelihood estimation (MLR) (Savalei, 2010). Based on the empirical evidence in favor of two models (as described in the introduction), we considered two models, displayed in **Figure 1**. Regarding CFA, **Table 3** provides an overview of the model fit statistics of the different factor structures. The first model we tested using CFA was a one-factor structure with all MABC-2 items (Model 1a). Model fit indices were found to be poor. Inspection of modification indices suggested that the model fit could be improved by allowing 'Posting Coins' and 'Threading Beads,' and 'Catching a Bean Bag' and 'Throwing a Bean Bag' to covariate. These modifications were justified from a theoretical point of view, since 'Posting Coins' and 'Threading Beads' are both speed items (Henderson et al., 2007). 'Catching a Bean Bag' and 'Throwing a Bean Bag' are both items that require control of fast-moving objects (Utley, 2019) and may be highly dependent on practice and experience (Henderson et al., 2007). Furthermore, these tasks correlated moderately with each other (*r* = 0.42 and *r* = 0.30, respectively, both $p < 0.01$). After adding these co-variances to the model, the one-factor model (Model 1b) revealed a good model fit (see **Table 3**). All factor loadings (λ) were statistically significant ($p < 0.01$; see **Table 4**), indicating they were good indicators of the latent factor. The second model (Model 2) we tested using CFA was the three-factor structure of the MABC-2 with 'Posting Coins,' 'Threading Beads,' and 'Drawing Trail' representing manual dexterity; 'Catching a bean bag' and 'Throwing a Bean Bag' representing aiming and catching skills; and 'One-leg Stand,' 'Walking on Toes,' and 'Jumping on Mats' representing balance.

TABLE 3 | Model fit statistics of the different factor structures of motor skills examined with CFA.

	χ^2 (*p*)	RMSEA	CFI	TLI	SRMR
Model 1a	53.62 (0.00)	0.09	0.80	0.72	0.06
Model 1b	30.61 (0.03)	0.06	0.92	0.88	0.05
Model 2	35.16 (0.01)	0.07	0.89	0.82	0.05

CFA: confirmatory factor analysis; Model 1a: one-factor structure; Model 1b: one-factor structure with modifications; Model 2: three-factor structure; RMSEA: Root Mean Square Error of Approximation; CFI: Comparative Fit Index; TLI: Tucker-Lewis Fit Index; SRMR: Standardized Root Mean Square Residual.

TABLE 4 | Factor loadings and residual errors of the motor and EF models.

One-factor motor model				Two-factor EF model			
Latent factor	**Items**	**Λ**	**ε**	**Latent factor**	**Items**	**λ**	**ε**
General motor skills	Posting Coins	0.44	0.81	Performance-based EFs	Day/Night	0.31	0.90
	Threading Beads	0.53	0.72		Hand Tapping	0.26	0.93
	Drawing Trail	0.40	0.84		Corsi Block	0.66	0.57
	Catch a Bean Bag	0.44	0.81		Digit Recall	0.59	0.65
	Throwing a Bean Bag	0.22	0.95		Conflict task	0.37	0.86
	One-leg Stand	0.54	0.71	Rating-based EFs	BRIEF-P Inhibition	0.88	0.23
	Walking on Toes	0.44	0.81		BRIEF-P Working Memory	0.81	0.35
	Jumping on Mats	0.38	0.86		BRIEF-P Cognitive Flexibility	0.47	0.78

BRIEF-P: Behavior Rating Inventory of Executive Function Preschool Version.

The model fit indices were found to be poor. Inspection of modification indices showed that the three-factor model could not be improved by allowing tasks to covariate. Using ESEM, convergence of the three-factor model (Model 2) could not be achieved because of a negative residual variance for 'Threading Beads.' In conclusion, the results indicated the existence of a one-factor structure with a latent general motor factor in this sample of 3- to 5-year-old children.

Factor Structure of EFs

As described in the introduction, we considered three models, displayed in **Figure 2**. Regarding CFA, **Table 5** provides an overview of the model fit statistics of the different factor models. The first model we tested using CFA was a one-factor structure with all performance-based and rating-based EF items (Model 1a). Model fit indices were found to be poor. Inspection of modification indices suggested that the model could be improved by allowing the 'Forward Digit Recall' and 'Forward Corsi Block' to covariate. These modifications were justified from a theoretical point of view, because these EF items both assess the ability of remembering and reproducing sequences of information (Pickering et al., 1998; Gathercole and Pickering, 2000) and correlated moderately with each other ($r = 0.39$, $p < 0.01$). After setting these co-variances to be free, the one-factor model (Model 1b) still showed poor model fit. The second model (Model 2) we tested using CFA was a three-factor structure with the 'Day/Night,' 'Hand Tapping,' and BRIEF-P Inhibition subscale representing inhibition; the 'Forward Corsi Block,' 'Forward Digit Recall,' and BRIEF-P Working Memory subscale representing working memory; and the 'Conflict Task' and BRIEF-P Cognitive Flexibility subscale. The model fit indices were found to be poor. Inspection of modification indices showed the three-factor model could not be improved by allowing tasks to covariate. Using ESEM, convergence of the three-factor model (Model 2) could not be achieved because of a negative residual variance for 'Day/Night.' The third model (Model 3) we tested using CFA was a two-factor model with the EF tasks representing performance-based EFs and the BRIEF-P subscales representing rating-based EFs. The model fit indices were found to be good. All factor loadings (λ) were statistically significant ($p < 0.01$; see **Table 4**), indicating that all EF items were good and unique indicators of the latent factors. The two-factor model (Model 3) was also examined using ESEM. Model fit indices were RMSEA = 0.00, CFI = 1.00, TLI = 1.02, SRMR = 0.03. In conclusion, CFA and ESEM supported the existence of a two-factor structure with a performance-based EF and a rating-based EF factor in this sample of 3- to 5-year-old children. The CFA model of the two-factor structure was used in further analysis, because of its parsimonious character and the unrealistically high model fit indices found with ESEM.

TABLE 5 | Model fit statistics of the different factor structures of EFs examined with CFA.

	χ^2 (*p*)	RMSEA	CFI	TLI	SRMR
Model 1a	64.77 (0.00)	0.11	0.80	0.72	0.10
Model 1b	45.24 (0.00)	0.08	0.88	0.82	0.09
Model 2	55.07 (0.00)	0.11	0.83	0.72	0.10
Model 3	20.80 (0.35)	0.02	0.99	0.99	0.05

Model 1: one-factor structure; Model 1b: one-factor structure with modifications; Model 2: three-factor structure; Model 3: two-factor structure; RMSEA: Root Mean Square Error of Approximation; CFI: Comparative Fit Index; TLI: Tucker-Lewis Fit Index; SRMR: Standardized Root Mean Square Residual.

Relationship Between Models of Motor Skills and EFs

The one-factor motor model (Model 1b) was related to the two-factor EF model (Model 3) by means of SEM (**Figure 4**). The model fit the data well (χ^2 = 117.87, RMSEA = 0.03, CFI = 0.95, TLI = 0.94, SRMR = 0.06). However, the latent factor of motor skills correlated non-significantly and weakly with the latent factor of performance-based EFs ($r = 0.26$, $p = 0.08$) and of rating-based EFs ($r = 0.16$, $p = 0.14$).

DISCUSSION

Main Findings

The current study investigated the task-specific and latent relationship between motor skills and EFs in preschool children. The correlations between specific motor and EF items showed

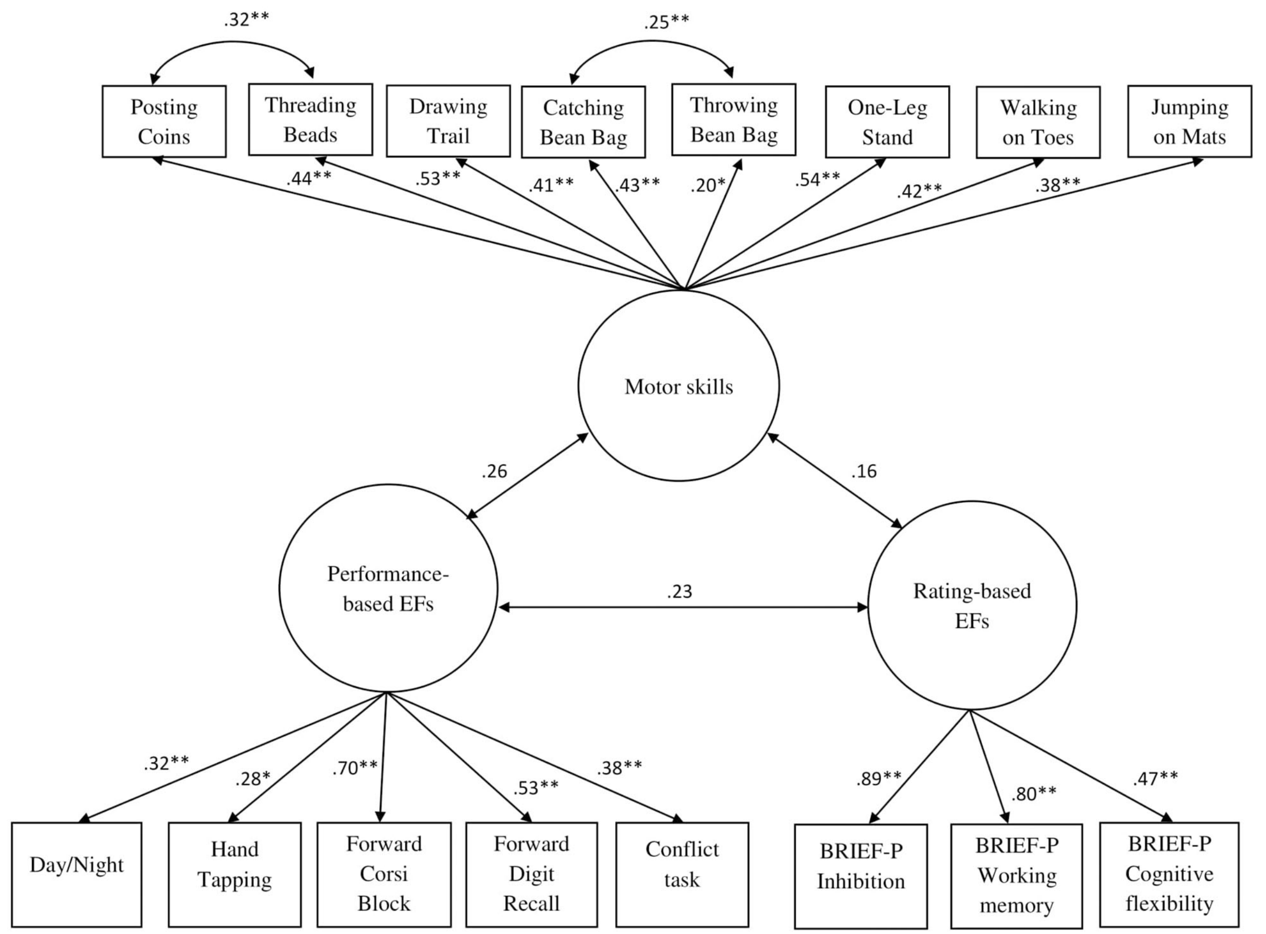

FIGURE 4 | Structural equation model of the relationships between motor skills and EFs. *$p < 0.05$; **$p < 0.01$.

significant albeit weak relationships between both domains, i.e., between all manual dexterity tasks and 'Hand Tapping'; and between the 'Drawing Trail,' 'One-Leg Stand,' and 'Jumping on Mats' tasks and the 'Forward Corsi Block.' There were no significant correlations between any of the specific motor items and the rating-based EF subscale scores. The SEM model revealed non-significant weak relationships between a general motor factor (as a unitary latent construct) and the latent constructs of performance-based EFs and rating-based EFs. There were no clear differences in results neither between the relationship between specific items of motor skills and EFs, nor between the unitary latent motor construct and latent components of EFs.

In line with the results concerning the task-specific relationships, Maurer and Roebers (2019) found significant weak relationships between the fine motor items of the MABC-2 and an inhibition task; and weak relationships between the 'Drawing Trail' and, the balance items of the MABC-2, and a working memory task in a sample of 5- to 6-year-old children. In contrast to our findings on an item-level, Maurer and Roebers (2019) obtained significant weak relationships between fine motor skills and a cognitive flexibility task. Oberer et al. (2017) reported more significant and stronger relationships between motor skills and EF tasks in a sample of 5- to 7-year-old children than the current study. Additionally, the results concerning the latent relationship differed from previous studies (Oberer et al., 2017; Maurer and Roebers, 2019). Oberer et al. (2017) showed strong relationships between gross motor skills and EF and Maurer and Roebers (2019) discovered moderate-to-strong relationships between these latent constructs. In addition, both of these studies showed strong relationships between a latent fine motor skills construct and a latent EF construct. The partly different results might be explained by the younger sample in our study compared to the samples of Maurer and Roebers (2019) and Oberer et al. (2017). Early development is characterized by non-linearity: Increases in performance in one developmental domain can be accompanied by decreases in performance in other developmental domains because the child has to divert energy toward the emerging skill at the expense of other areas (Ben-Sasson and Gill, 2014). However, stability of development seems to increase with age (Schneider et al., 2014). Relationships between motor skills and EFs may therefore become stronger as a function of age. In addition, due to discontinuity in (early) development, relationships between motor skills and EFs may be weaker cross-sectionally compared to longitudinally.

Another explanation for the weak relationships between motor skills and EFs in young children may be found in the role child and environmental factors may play in both domains and their relationship. In light of embodied cognition theories, the relationship between motor skills and EFs is shaped by features of the physical body and grounded in the unique experiences within the environment (Adolph and Hoch, 2019). In this context, it could imply that relationships between motor skills and EFs differ per specific subgroups of children. For example, previous studies have demonstrated that gender, attention, ADHD symptomatology, and SES confounded the relationship between motor skills and EFs (Wassenberg et al., 2005; Piek et al., 2008; Houwen et al., 2017). In addition, several studies have mentioned the possible effect of moderators, such as gender, non-verbal intelligence, reaction time, visual perception, and fitness (Aadland et al., 2017; Michel et al., 2018). The potential role of child characteristics and environmental factors as confounding variables and moderators thus need to be taken into account when examining the relationship between motor skills and EFs.

The inconsistent results found in empirical studies (Livesey et al., 2006; Michel et al., 2011; Lehmann et al., 2014; Roebers et al., 2014; Stöckel and Hughes, 2016; Fang et al., 2017; Houwen et al., 2017; Oberer et al., 2017; Alesi et al., 2019; Cook et al., 2019; Maurer and Roebers, 2019), including the current study, may be partially explained by the use of different motor and EF measures. Measurement selection is important when latent relationships are examined, because the common variance across multiple measures captured by latent variables may include measurement error resulting from unintendedly measured common additional processes, such as attention and language comprehension (Friedman and Miyake, 2017). Miller et al. (2012) showed that the structure of EF examined with CFA was influenced by measurement selection in a sample of preschool children. Different factor structures, as a result of different selection of measures, may, subsequently, lead to different latent relationships. In addition, the selection of measures may have influenced the results regarding the task-specific relationships. Measurement selection is a challenge for researchers, especially the selection of EF tasks, because numerous performance-based EF measures have been developed for use in preschool children (Ackerman and Friedman-Krauss, 2017). However, many of these measures have not been thoroughly evaluated for psychometric properties (Willoughby and Blair, 2016). The current study included performance-based EF measures that have shown good internal consistency and/or test-retest reliability in preschool children indicating good psychometric properties (Alloway et al., 2006, 2009; Chasiotis et al., 2006; Thorell and Wåhlstedt, 2006; Blair and Razza, 2007; Bierman et al., 2008; Rhoades et al., 2009; Beck et al., 2011; Müller et al., 2012).

Limitations

There are some limitations that should be taken into consideration when interpreting the results. First, age and gender were not included in the analysis of the factorial structures and relationships between both domains. Although multi-group invariance testing demonstrated that the correlational data of the age groups could be aggregated, age and gender may have an effect on the results. For example, the factor structure might differ per age group and gender with the consequence that the analyses should be performed per age group and gender, and may result in differential relationships. Unfortunately, although there are no explicit guidelines for the minimum sample size required to examine measurement invariance in factor structure, research into the required minimum sample size for CFA implies that the sample size of the current study was too small to evaluate measurement invariance of the factor structures of motor skills and EFs (Kyriazos, 2018). Thus, we could not examine the potential influence of age and gender on the relationship between both domains. Second, the data contained some missing values (6.6%) which reduced the statistical power and may have led to biased estimates (Kang, 2013). In our study, the missingness was related to observed variables (namely age and gender), which supports the use of multiple imputation under missing at random conditions (Graham, 2009). We attempted, however, to reduce the impact of missing data by using multiple imputation for the correlation analyses and robust maximum likelihood estimation for the CFAs, ESEMs, and SEM. Third, convergence could not be achieved by ESEM for the three-factor model of motor skills and the three-factor model of EFs. The failure of convergence was probably due to an issue regarding the item 'Threading Beads' (regarding the motor model) and the 'Day/Night' task (regarding the EF model). The failure of convergence might have been caused by measurement errors. The speed element of the item 'Threading Beads' might not have been understood well by the preschool children as observed regularly by the test administrators in this study. Regarding the 'Day/Night' task, many preschool children have difficulty remembering the rules of this task (Diamond et al., 2002). Fourth, the weak relationships found using SEM were non-significant. The sample size may have been too small to show significant relationships using SEM. *P*-values are highly dependent on sample size and should therefore be interpreted with caution (Cohen, 1990; Cumming, 2014).

Future Directions and Implications

The fact that only weak relationships were discovered in the current study suggests that motor skills and EFs may be distinct developmental domains at preschool age. In addition, the findings suggest that it may be important that children with both motor and EF difficulties receive intervention targeted at both developmental domains. Intervention studies, however, showed that interventions targeting motor skills had positive effects on EFs in young children (Zoghi et al., 2016; Mulvey et al., 2018). Clearly, more research is required to gain more insight into whether interventions focused on only one developmental domain, such as motor skills, result in sufficient improvement in both developmental domains, or whether interventions focused on both motor skills and EFs are required to be effective in young children. Furthermore, future longitudinal research is needed to explore whether relationships between motor skills and EFs in young children exist over time. Additionally, it would be worth examining the role of potential confounding and moderating factors in the relationship between motor skills and EFs, such as gender, attention, and fitness (Wassenberg et al., 2005; Aadland et al., 2017; Houwen et al., 2017).

The current study's findings did not confirm the three dimensional structure of the MABC-2 proposed by Henderson et al. (2007). Instead, our study indicated a one-factor structure of motor skills. Although some studies supported the three-factor structure of the MABC-2 in preschool children (Ellinoudis et al., 2011; Psotta and Brom, 2016), other studies did not confirm its three-factor structure in preschool children (Schulz et al., 2011; Hua et al., 2013; Kokštejn et al., 2018). In line with our findings, Schulz et al. (2011) found a one-factor structure supporting the notion of a general motor ability in preschool children (Hands et al., 2018). It remains to be seen whether the factor structure proposed by Henderson et al. (2007) is an appropriate representation of the motor construct in 3- to 5-year-old children. Therefore, we suggest that researchers and professionals in the clinical field should carefully interpret the separate components of young children's MABC-2 performance. In addition, it is recommended to investigate the factor structure of motor skills and EF in a larger sample and examine its invariance across age and gender.

The current study found support for a two-factor structure of EFs consisting of performance-based EFs and rating-based EFs. These findings are difficult to compare to previous studies as previous studies did not include rating-based EF measures in their studies about the structure of EFs (Wiebe et al., 2008; Shing et al., 2010; Willoughby et al., 2010, 2012; Fuhs and Day, 2011; Masten et al., 2012; Miller et al., 2012; Usai et al., 2014; Monette et al., 2015). The non-significant to significantly moderate relationships between performance-based and rating-based EFs that have been found in earlier studies may imply that these types of measures provide different information regarding preschool children's EFs (Miranda et al., 2015; O'Meagher et al., 2019; Tamm and Peugh, 2019). Therefore, depending on what aspect of EFs is intended to be examined, it is important to make well-considered decisions regarding the choice of an EF measure. In order to provide a comprehensive picture of EFs in preschool children, it is useful to use both types of EF measures such as the BRIEF-P (Gioia et al., 2005) and an EF task battery. Recently, standardized task batteries have been developed to assess EFs. For future research it is recommended to use such a measure, such as the Executive Function Touch (Willoughby and Blair, 2016).

CONCLUSION

This study offers a comprehensive examination of task-specific and latent relationships between a range of motor skills and EFs in preschool children. Weak relationships between specific motor and EF items and weak latent relationships suggest that motor skills and EFs may be distinct developmental domains at preschool age. It remains to be seen in longitudinal studies whether the relationship between motor skills and EFs changes as a function of time.

DATA AVAILABILITY STATEMENT

The datasets generated for this study will not be made publicly available this study is part of a larger research project which is still ongoing.

ETHICS STATEMENT

The study protocol was approved by the Ethics Review Committee of the Department of Pedagogical and Educational Sciences, Faculty of Behavioural and Social Sciences, University of Groningen. All parents gave written informed consent in accordance with the Declaration of Helsinki.

AUTHOR CONTRIBUTIONS

GV was responsible for the data collection, conducted the analysis, and wrote and edited the manuscript. EK was responsible for the data collection and contributed to the analysis and reviewing the manuscript. MC, AM, and SH supervised the study, and contributed to the writing and reviewing of the manuscript. All authors contributed to the article and approved the submitted version.

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Cross-Sectional Study Using Virtual Reality to Measure Cognition

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Dual-task research is limited in its transferability to authentic contexts because laboratory conditions do not replicate real-world physical activity and decision-making scenarios. Creating valid, reliable methodologies to assess physiological and behavioral responses under varying physical and cognitive demands using virtual reality (VR) environment addresses this limitation. This study determined the feasibility of using VR to investigate the effects of dual-tasking on healthy young adults' cognitive performance. Three dual-tasking conditions (i.e., standing, preferred-paced walking, and fast-paced walking, each with blocked congruent and incongruent tasks) were developed. Using a within-subjects, randomized design, thirty-two young adults (17 female, mean age = 21.03 ± 2.86) were randomly assigned to a starting condition but experienced all three conditions. Physiological responses of heart rate (HR) and accelerometry data measured energy expenditure as the physical demand. Behavioral responses of reaction time and error rate quantified cognitive performance. Results indicated that (a) each condition verified independent physiological and behavioral responses; (b) reaction time and error rate during preferred walking or fast-paced walking dual-tasking conditions was significantly lower than standing condition; and surprisingly, (c) congruent tasks showed lower reaction time than the incongruent tasks. These findings suggest that it is feasible to use VR to assess the effects of dual-task conditions. Specifically, walking can optimize the motor-cognitive dual-task performance, compared to standing. These findings may be attributed to the dose-response effects of exercise intensity. Future studies should incorporate advanced technology such as the VR exercise.

Keywords: dual-tasking, cognitive-motor interference, cognition, exercise, virtual reality, behavior response, exercise intensity, cognitive demand

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INTRODUCTION

Technological advances have manifested a need for increased inhibitory control, given the number of stimuli experienced by humans in daily living. The intensified demand for information processing affects decision-making (Crone and Dahl, 2012) and cognitive reasoning (Houdé and Borst, 2014, 2015). Although people may think of themselves as such, humans are not multitaskers. Instead, humans shift attention between tasks while focusing on a primary stimulus and blocking out distractions that may emerge from secondary stimuli. For example, a driver needs to selectively attend to the Global Positioning System (GPS) information that simultaneously provides a visual map and verbal directions requiring a motor response. Humans uniquely process each piece of information first through the source of the stimuli (e.g., sight, sound, touch, and/or smell) and then by discriminately prioritizing the information they believe has the most significant relevance to their goal. Most decisions like the one just described are considered automatic information processing and therefore considered cold cognition (Leshem et al., 2020). Although some cognitive decisions are both complex and influenced by emotion, all of the conditions in this research study were classified as cold cognitive decisions. Further, given the minimal risk of performing each task, little emotion was involved.

Background/Rationale

When humans are asked to perform two tasks simultaneously, the two tasks are executed interdependently. However, because they have distinct and separate goals (Sigman and Dehaene, 2008), it is called dual-tasking. The study of dual-tasking has been around for some time. With the emergence of virtual reality (VR) and an interest in the effects of acute exercise on cognitive performance, new paradigms and conceptual frameworks are beginning to emerge. Most studies currently reflect the traditional assumption that dual-tasking deteriorates the performance on one or both tasks because an individual has limited resources for cognitive processing (Kahneman, 1973). The underlying premise of dual-tasking studies is that resources are limited, and when they have to be shared between two tasks simultaneously, performance will degrade relative to when and how often each task is performed (Plummer and Eskes, 2015; Herold et al., 2018). Conversely, some studies have shown that dual-tasking that includes a motor task may benefit motor or cognitive performance (Altmann et al., 2015; Hazamy et al., 2017; Studer, 2018). For example, Altmann and colleagues found an improvement in motor performance during cognitive dual-tasks. Therefore, it is unclear how different types of exercise with varying physiological demands may influence cognitive performance, especially in real-world scenarios represented in VR environments.

Recently, the dual-tasking paradigm has been applied to understand the effects of texting and driving or walking. As previously mentioned, a driver must shift their attention between the two competing tasks. A pedestrian who uses a cell phone while walking is more susceptible to being involved in an accident because of delayed responses and increased variability of responses when navigating objects on the phone screen and within the walking space (Chopra et al., 2018). This relative change in performance associated with dual-tasking is referred to as *dual-task interference*. In a given moment, the required resources used to process information are available in fixed quantities. Thus, performance suffers when resources are exceeded by the demands of the task (Gopher and Navon, 1980). Given the competing demands for limited resources, conditions that elicit dual-task interference are generally used to assess cognitive abilities in the field of rehabilitation and gait studies.

There are additional plausible reasons for performance to deteriorate in dual-tasking conditions like walking and talking (e.g., Neider et al., 2011; Holtzer et al., 2014) or thinking while moving (Schaefer et al., 2015; Herold et al., 2018), which could be attributed to the motor-cognitive demands. Schaefer (2014) summarized three potential explanations for the dual-task interferences with different foci of interest. The first possible explanation is the *prioritization of walking* that the motor task is prioritized over cognition, because the motor task involves some threat to balance and risk of falling (Plummer and Eskes, 2015), such as prioritizing walking over talking on the phone (Verghese et al., 2007). The second potential explanation of dual-processing is *sensorimotor-cognitive interactions*. When comparing young and older adult participants in dual-tasking, older adults' limited resources led to increased walking instability, while young adults continue to show stable motor performance levels (Verrel et al., 2009; Schaefer, 2014). The underlying premise is that sensorimotor performance requires increased attentional resources with advanced age. Hence, most studies revealed that aging is the main contributing factor to gait balance, leading to cognitive decline under dual-task structure (Craik and Salthouse, 2011). The third explanation is related to the *beneficial effect of exercise on cognitive performance*. Even though most studies in this field assessed the cognitive benefits immediately after exercise, dual-tasking, like making decisions while playing a sport, may lead to the reallocation of attentional resources (Kamijo et al., 2009; Best, 2010; McMorris, 2015). As previously noted, various factors may influence dual-tasking situations, such as task difficulty, aging, arousal level, and postural threat. Despite these known effects, interference is often inadequately measured in dual-tasking studies, limiting what the researchers currently know about the effect of dual-task performance.

There are many dual-task studies focused on understanding the association between cognitive decision making and walking tasks (Al-Yahya et al., 2011; Schaefer, 2014); however, most of the studies have utilized a cognitive task that was not directly associated with the movement or with the real-world context (e.g., solve computational problems while walking). Further, the outcomes were indirectly extrapolated. No study to date has investigated the effects of cognitive tasks integrated into VR facilitated exercise conditions. Given the limitations of current methodologies, the direct effects of varying cognitive demands on motor performance remain unclear, and researchers still lack the knowledge and consistent application of cognitive tasks applicable to clinical and real-world settings. The present study attempts to address such identified gaps in the research by examining dual-task performance through direct measurement of behavioral and physiological responses during life-like conditions requiring differing cognitive demands. The researchers developed simulated real-world conditions that manipulated the difficulty of cognitive tasks and the amount of energy expended within each condition using an integrated VR environment and treadmill that mimics common everyday experiences (e.g., participant walks down a path and avoids or interacts with objects).

Objectives

This study aimed to determine the feasibility of using VR to investigate the effects of dual-tasking on healthy young adults' cognitive performance. The research team developed three different VR conditions: (a) standing on a path and experiencing a block of congruent tasks followed by a block of incongruent tasks, (b) walking at a preferred speed down a path and experiencing a block of congruent tasks followed by a block of incongruent tasks, and (c) fast-paced walking down a path and experiencing a block of congruent tasks followed by a block of incongruent tasks. In accordance with previous dual-task research (Li et al., 2005), we hypothesized that participants would require more cognitive resources during walking and fast-paced walking than during a standing condition due to the prioritization of walking. Further, it was hypothesized that the incongruent task would require more attentional resources than congruent tasks, which would be reflected as slower reaction times and an increased frequency of error.

METHODS

Study Design

The study used a within-subject randomized design. Upon study approval by the Institutional Review Board at The University of Texas at Austin (IRB #2019-12-0107), potential participants were screened for eligibility. Those meeting the inclusion criteria came to the lab for one 90 min visit, completed a health screening questionnaire, baseline measures, and familiarization with the VR environment. Once comfortable with the VR, each participant experienced all three exercise conditions (**Figure 1**). During each condition, the researchers measured behavioral and physiological responses.

Participants

Thirty-two self-reported healthy young adults (M age = 21.03 ± 2.86 years, 17 Females) participated (**Table 1**). Participants were recruited via flyers, online advertisements, and public announcements from central Texas. The participant's ages ranged from 19 to 29 years, and because each participant reported no adverse health characteristics, they were likely to have a level of physical fitness that would allow for an age-appropriate HR recovery between conditions. All participants were screened to ensure they had no history of falls, cardiovascular, neurological, or visual deficits that might have affected their walking ability. Physical health assessments, including HR, height, weight, and self-paced preferred walking speed (PWS), were measured before the participant was randomly assigned to the initial condition. Each participant received $20 for their participation.

Setting: Virtual Reality (VR) Environment

The VR lab has a 1 m wide × 2 m, split-belt treadmill with an integrated VR projection screen to create authentic dual-tasking situations (Motekforce Link, Amsterdam, Netherlands). The VR scene was projected onto a 3-meter tall 180° degree semi-cylindrical screen in front of the treadmill (**Figure 2**). During the dual-tasking conditions, the screen displayed a computer-generated "trail road" environment through D-Flow software (Geijtenbeek et al., 2011), which realistically simulates the feel of being in the scenario. All participants wore a safety harness (Petzl, Crolles, and France) to prevent falls, and they were instructed to look straight ahead to the VR screen and avoid extraneous movement. Preferred walking speed (PWS) was measured before the dual-tasking condition. To assess the PWS and acclimate the participant to the VR, each participant walked for 5 min at various treadmill speeds. PWS was determined by starting from a relatively slow pace and slowly increasing the treadmill speed until the participant reported that the current speed felt "comfortable" without additional effort. This procedure was repeated three times and the average of the 3 "comfortable" speeds was taken as the participant's PWS.

Motor-Cognitive Dual-Tasking

All participants experienced the three different VR dual-tasking conditions requiring the participant to avoid or interact with an object in their path: *standing congruent/incongruent; preferred-paced walking congruent/incongruent, and fast-paced walking congruent/incongruent*. The motor portion of the dual-task was exercise. Gait speed was used to manipulate exercise intensity in each exercise condition. Measures of heart rate (HR) and step counts confirmed the exercise intensity. The researchers established that low to moderate-intensity exercise corresponds to standing, whereas higher intensity exercise corresponds to fast-paced walking. During walking or fast-paced walking conditions, participants were instructed to walk at a PWS or 25% faster-walking speed than PWS on the VR treadmill, respectively.

The cognitive portion was based on two existing cognitive paradigms, the Go/No-Go and Oddball. The classic Go/No-Go paradigm (Gomez et al., 2007) examines response inhibition and response competition. In a typical Go/No go experiment, participants are instructed to respond by the keypress to the go stimulus and withhold responses to the No-Go stimulus (Ríos-Lago and Periáñez, 2010). Here, in this study, the participants are asked to interact with or avoid objects in the VR environment. The oddball paradigm (Picton, 1992) examines behavioral and neural responses to novel events. In this paradigm, an improbable series of unique and unexpected novel events are presented, in addition to targets and standards (Ríos-Lago and Periáñez, 2010). As an adaptation of this paradigm, a total of 60 colored target stimuli were displayed on the VR screen, with each object appearing on the screen for 3–5 s intervals. Additionally, visual and auditory feedback were given as each target was encountered.

The first block of 60 trials required the participant to interact with 80% of the objects, which was considered a congruent task. Once the block of congruent tasks was completed, the participant stood for 1 min to receive the opposite directions. The second set of directions required the participant to interact with the object they previously had to avoid (20%), thus reversing the expected behavioral response and introducing interference into the information processing. A congruent task was always introduced first, followed by the corresponding incongruent task for the same exercise mode and intensity to establish an expected behavioral response. The paired patterning of congruent and incongruent was necessary to introduce interference as the incongruency.

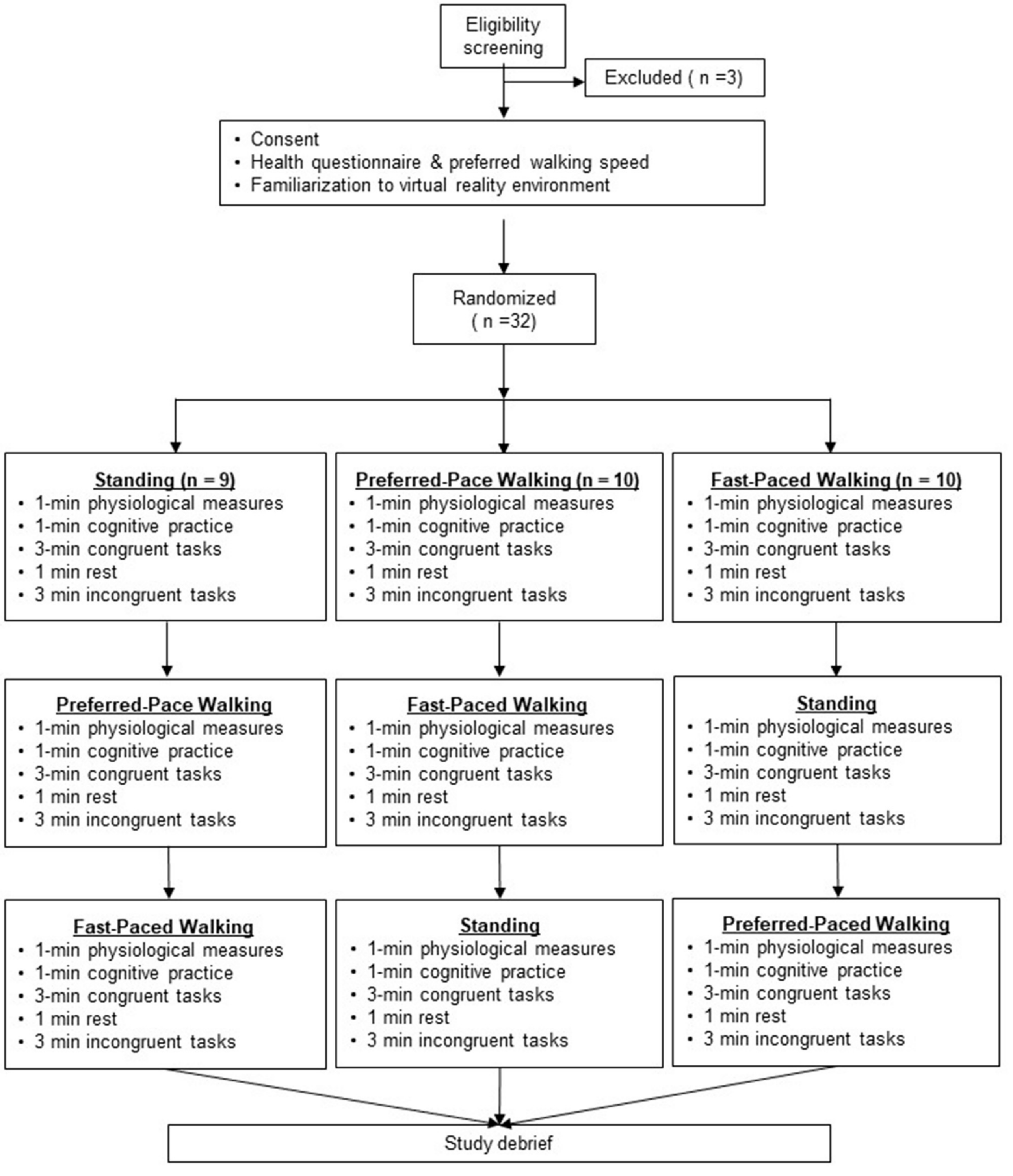

FIGURE 1 | Summary of study protocol and randomization.

Measuring Behavioral and Physiological Responses

Cognitive performance was the dependent variable and was quantified by measuring reaction time and error rate. Behavioral responses of the reaction time and the percentage of error were calculated during dual-tasking conditions: (a) mean reaction time of correct responses and (b) mean percentage of incorrect responses to the non-target stimuli and missed target stimuli.

The target stimuli were presented for 3,000 ms. If the participant did not identify a correct response within 3 s, it was considered incorrect. Only the correct responses were used as data for the reaction time. Physiological responses of step counts and HR were tracked using an Actigraph GT3X accelerometer (Santos-Lozano et al., 2013) and a Polar HR monitor (Ceesay et al., 1989). In combination, these data provided a total volume and intensity of exercise, thus allowing us to compare the physiological effects of different conditions.

An integrated 10 camera Vicon motion capture system (Oxford Metrics, Oxford, UK) and D-Flow software recorded the participant's movement to project it on to the screen. The participants wore gloves with hand markers that captured reaction time and error rate to collect the behavioral response data. The reaction time was the lapse time from when the object appeared on the screen when there was a correct response. An error was considered to be an incorrect response or no response at all. The number of incorrect responses and missed targets were divided by the number of total trials in a condition to calculate the error rate.

TABLE 1 | Participant Characteristics.

Variable	Total ($n = 29$) M (SD)	Male ($n = 15$) M (SD)	Female ($n = 14$) M (SD)
Age	21.24 (2.86)	22.33 (3.24)	20.07 (1.86)
Height (cm)	170.06 (8.47)	175.93 (6.46)	163.76 (5.18)
Body Mass (kg)	71.90 (13.80)	75.78 (13.83)	67.73 (12.95)
Body Mass Index (kg/m$^{2)}$	24.78 (3.84)	24.39 (3.65)	25.19 (4.12)
HR resting (beat/min)	71.17 (15.14)	65.87 (12.72)	76.85 (15.89)
Preferred Walking Speed (m/s)	1.46 (0.18)	1.47 (0.22)	1.45 (0.13)

Fatigue and Order Effect

Performance could be influenced by fatigue or a learning effect. To address these concerns, the participants were randomized into one of three possible starting points in the series of exercise conditions (**Figure 1**). Because an incongruent task must always follow a congruent task in order to establish an expectation of behavior, the randomization needed to be limited to these specific points. It is unlikely that cognitive fatigue played a role in this study, given the short duration of all activities and no increase in error rate in the final block of trials across all participants and conditions.

Study Size

A power analysis (Erdfelder et al., 1996) indicated that a total sample of 24 participants would be needed to detect an effect size of 0.30 with 80% power using a repeated measure ANOVA. This would have a similar power from a previous study that tested the effects of acute exercise on cognitive performance with 2 x 2 mixed design used with an effect size of 0.31, with the power of 0.80 (Chang et al., 2014). Complete data from 32 total participants were obtained and analyzed to be conservative.

Data Analysis

Data were visually reviewed, audited, and then scrutinized using descriptive statistics to confirm normality. First, each condition was compared using analysis of variance (ANOVA) with repeated measures. Second, the average step counts and HR as physiological responses were analyzed using a one-factor (Exercise Intensity) ANOVA with repeated measures.

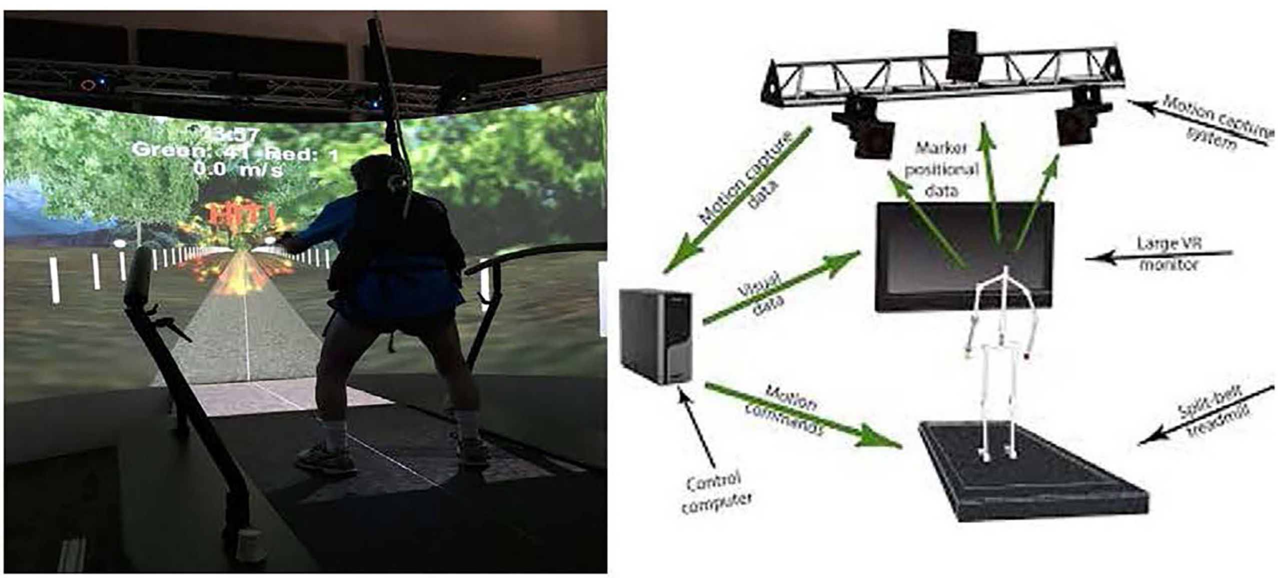

FIGURE 2 | Visual and auditory feedback through VR screen during the dual-tasking condition.

TABLE 2 | Physiological and Behavioral Measures.

Physiological Variables	Standing M (SD)	Walking M (SD)	Fast-paced walking M (SD)	*p*-value
HR, beats/min	85.71 (17.35)	102.93 (17.79)	121.12 (23.47)	<0.01**
Step counts	0.60 (1.15)	463.68 (30.10)	518.07 (33.81)	<0.01**
Behavioral Variables	**Standing M (SD)**	**Walking M (SD)**	**Fast-paced walking M (SD)**	***p*-value**
Reaction time (sec)	0.63 (0.05)	0.58 (0.04)	0.59 (0.05)	<0.01**
Error rate (%)	13.11 (9.07)	2.84 (3.51)	4.06 (4.70)	<0.01**
Behavioral Variables		**Congruent M (SD)**	**Incongruent M (SD)**	***p*-value**
Reaction time (sec)		0.59 (0.04)	0.62 (0.05)	<0.01**
Error rate (%)		7.30 (4.86)	6.03 (4.99)	0.18

*Values are mean (SD). Significance difference by Bonferroni post hoc analysis, **p < 0.01: standing vs. walking, **p < 0.01: standing vs. fast-paced walking, **p < 0.01: walking vs. fast-paced walking.*

Also, each condition was compared using a paired-samples *t*-test to interpret the higher-order condition. Finally, behavioral responses of reaction time and error rate were analyzed using two-factor (Exercise Intensity × Cognitive Task) with repeated measures. When sphericity was violated in the ANOVA, the Greenhouse-Geisser correction was applied. *Post hoc* tests using the Bonferroni correction were performed to determine the location of significance. Differences were considered significant at $p < 0.05$. When a difference reached significance, the effect size was calculated *via* Cohen's d or partial eta-square ($\eta_p{}^2$).

RESULTS

Participants

Of the 32 participants, a total of 29 participants completed the experimental sessions. Three participants did not complete the study. Two individuals had scheduled commitments and had to leave before the assessments were completed, and a third participant withdrew because of the perceived difficulty of testing conditions. Thus, all tasks were completed, and there were no missing trials with the 29 participants, whose data were included in the final analysis.

Effect of Exercise Intensity During Dual-Tasking Conditions on Physiological Responses

The means of HR and step counts between conditions are presented in **Table 2**. The standing condition was excluded from this analysis because there was no significant variation in the number of steps detected across the participants. Instead, descriptive statistics were reported for the reference of full dual-tasking conditions (standing M HR = 85.71, SD = 17.35; standing M step counts = 0.60, SD = 1.15). A paired-samples t-test was used to determine whether there was a significant mean difference between walking and fast-paced walking conditions. There was a significant difference between dual-tasking conditions at each same gait speed on HR (walking: $M = 102.93$, $SD = 17.79$, fast-paced walking: $M = 121.12$, $SD = 23.47$, respectively; $SE = 2.18$, $t(28) = 8.33$, $p < 0.01$, $d = 1.55$, **Figure 3**) and step counts (walking: $M = 462.86$, $SD = 29.89$, fast-paced walking: $M = 517.81$, $SD = 33.23$, respectively; $SE = 3.82$, $t(28) = 14.38$, $p < 0.01$, $d = 2.67$). Although step counts for standing conditions should be "zero," the sensors did detect a small motion artifact as participants moved over their bodies while standing, so some data shown were not exactly "zero." Following the ActiLife software, the motion artifact does not change the movement classification of "zero" steps.

Effect of Dual-Tasking Conditions on Behavioral Responses

The reaction time and error rate for both congruent and incongruent tasks during treadmill exercise are presented in **Table 2**. There were no outliers, as assessed by examination of studentized residuals for values higher than ±3. The reaction time and error rate were normally distributed, as assessed by Shapiro-Wilk's test of normality on the studentized residuals ($p > 0.05$). Mauchly's test of sphericity indicated that the assumption of sphericity was violated for the two-way interaction, χ^2 (2) = 7.66, $p = 0.02$. Therefore, we reported significance for the F values after the Greenhouse-Geisser correction.

A two-way repeated measures ANOVA was calculated to determine the effect of each dual-tasking condition on reaction time. There was a significant two-way interaction between exercise intensity and cognitive task [$F_{(1.60,\ 44.91)} = 3.56$, $p < 0.05$, $\eta_p{}^2 = 0.11$] on reaction time (**Figure 4**). Therefore, simple main effects were run. First, a simple main effect for cognitive tasks for differences in reaction time between conditions at the same level of exercise intensity was run. Three separate tests were analyzed using one-way repeated measures ANOVA. Mean reaction time was 0.045 s, 95% CI [0.024–0.066] faster at the standing congruent task as opposed to the standing incongruent task, a significant difference, $F_{(1,\ 28)} = 18.95$, $p < 0.01$, $\eta_p{}^2 = 0.40$. Mean reaction time was 0.018 s, 95% CI [0.005–0.032] faster at the walking congruent task as opposed to the walking incongruent task, a significant difference, $F_{(1,\ 28)} = 7.51$, $p = 0.011$, $\eta_p{}^2 = 0.21$. Mean reaction time was 0.025 s, 95% CI [0.014–0.037] faster at the fast-walking congruent task as opposed to the fast-walking incongruent task, a significant difference, $F_{(1,\ 28)} = 19.65$, $p < 0.01$, $\eta_p{}^2 = 0.41$. *Post hoc* tests using the Bonferroni correction indicated that mean reaction time was significantly faster at the congruent task ($M = 0.59$, SD

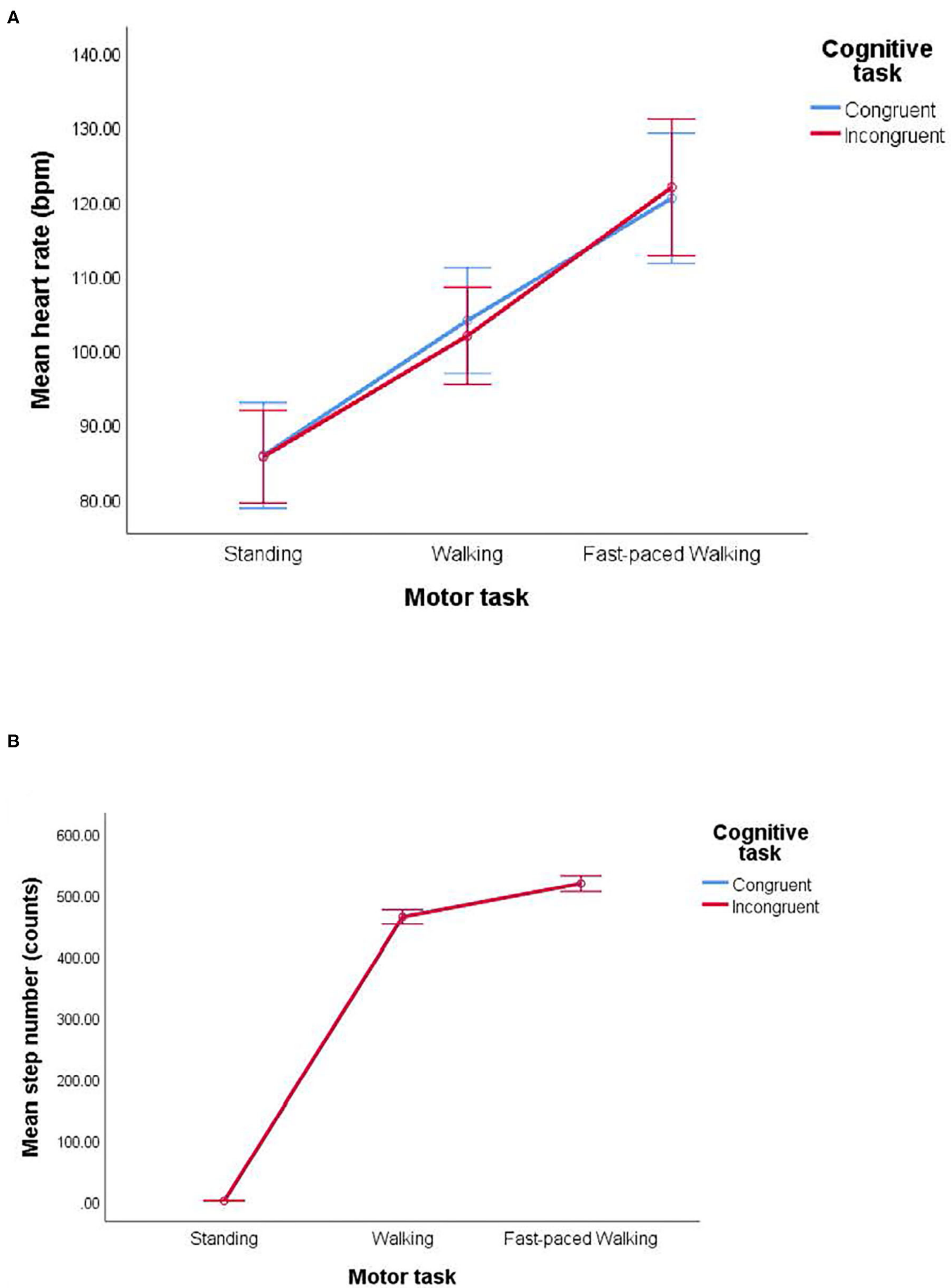

FIGURE 3 | Physiological responses of **(A)** heart rates and **(B)** step counts during VR dual-tasking conditions.

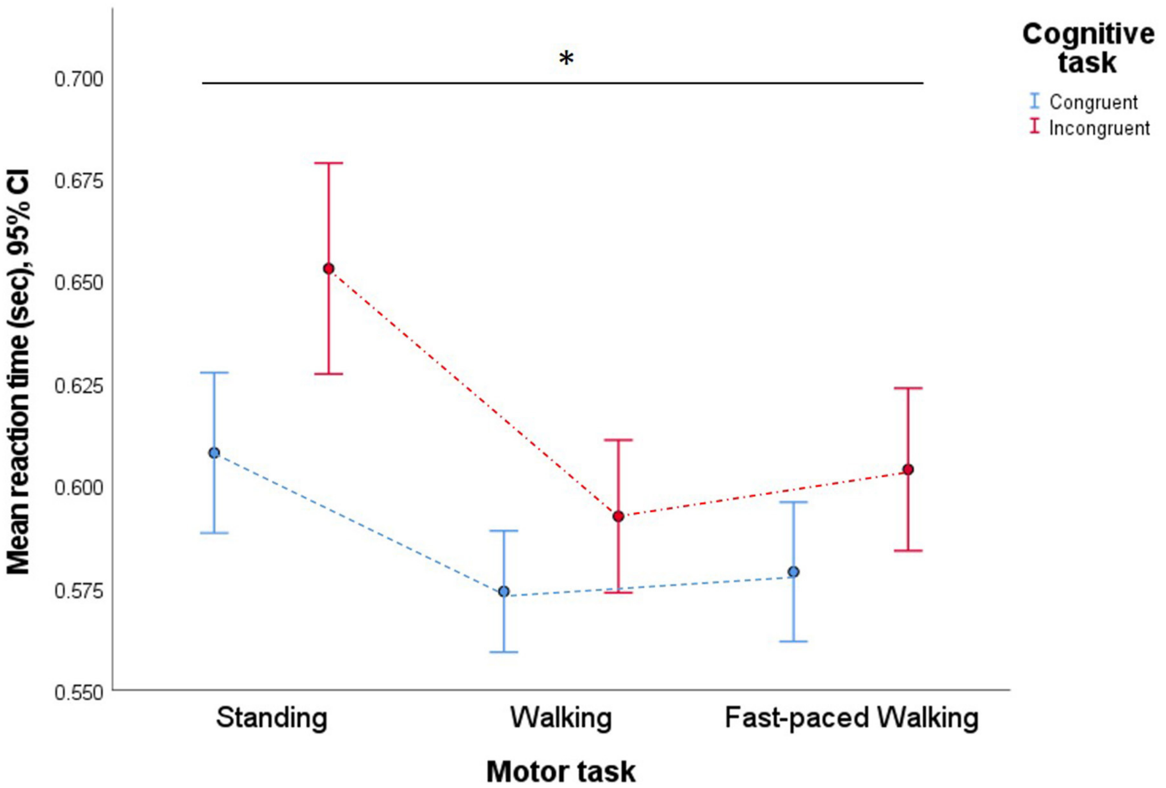

FIGURE 4 | Means reaction time for the congruent and the incongruent task in all VR dual-tasking conditions. Figure showing two-way interaction between motor task and cognitive task on reaction time (*$p < 0.05$).

$= 0.04$) than the incongruent task ($M = 0.62$, $SD = 0.05$), $F_{(1, 28)} = 34.31$, $p < 0.01$, $\eta_p{}^2 = 0.55$, a difference of 0.03 s, 95%CI [0.02–0.04]. Second, a simple main effect for exercise intensities for differences in reaction time between conditions at each level of the same cognitive task was run. Two separate tests were analyzed using one-way repeated measures ANOVA. Mean reaction time was significantly changed over the different intensity of exercise in the congruent task, $F_{(2, 56)} = 11.64$, $p < 0.01$, $\eta_p{}^2 = 0.29$. There was also a significant effect of different intensity of exercise in the incongruent task, $F_{(2, 56)} = 25.65$, $p < 0.01$, $\eta_p{}^2 = 0.48$. *Post hoc* tests using the Bonferroni correction indicated that mean reaction time was significantly faster during the walking condition ($M = 0.58$, $SD = 0.04$), a difference of 0.05 s, 95% CI [0.03–0.06] and fast-paced walking condition ($M = 0.59$, $SD = 0.05$), a difference of 0.04 s, 95% CI [0.02–0.06] than standing condition ($M = 0.63$, $SD = 0.05$), $F_{(1.50, 42.02)} = 30.18$, $p < 0.01$, $\eta_p{}^2 = 0.52$. However, there was no difference between walking and fast-paced walking conditions ($p = 0.32$).

A second two-way repeated measures ANOVA was conducted to determine the effect of each dual-tasking condition on the error rate. There was no significant two-way interaction between exercise intensity and cognitive task [$F_{(1.30, 36.47)} = 2.07$, $p = 0.16$, $\eta_p{}^2 = 0.07$] on error rate (**Figure 5**). The main effect of exercise intensity showed a significant difference in error rate between conditions, $F_{(1.36, 38.20)} = 29.33$, $p < 0.01$, $\eta_p{}^2 = 0.51$. *Post hoc* tests using the Bonferroni correction indicated that mean error rate was significantly higher in the standing condition ($M = 13.11$, $SD = 9.07$) than walking condition ($M = 2.84$, $SD = 3.51$), a difference of 10.27 percentages, 95% CI [5.84–14.70] and fast-paced walking condition ($M = 4.06$, $SD = 4.70$), a difference of 9.05 percentages. However, the main effect of cognitive task showed that there was no significant difference in error rate between conditions, $F_{(1, 28)} = 1.92$, $p = 0.18$, $\eta_p{}^2 = 0.06$.

DISCUSSION

To the best of our knowledge this is the first dual-tasking study using the VR environment to measure congruent and incongruent tasks during exercise. Three different dual-tasking conditions were developed to offer varying exercise intensities and cognitive demands. Our findings indicated four main things. First, we confirmed that using VR is feasible and produces the physiological response that were anticipated. Second, the motor task with different intensities of exercise affects the behavioral response.

Contrary to our hypothesis, however, walking and fast-paced walking conditions on the VR treadmill led to significantly faster reaction time and a lower error rate than the standing condition. Third, the congruent task elicited faster reaction times but not lower error rates than the incongruent task. There was also an interaction effect on reaction time combined with the physical and cognitive demanding conditions but not on error

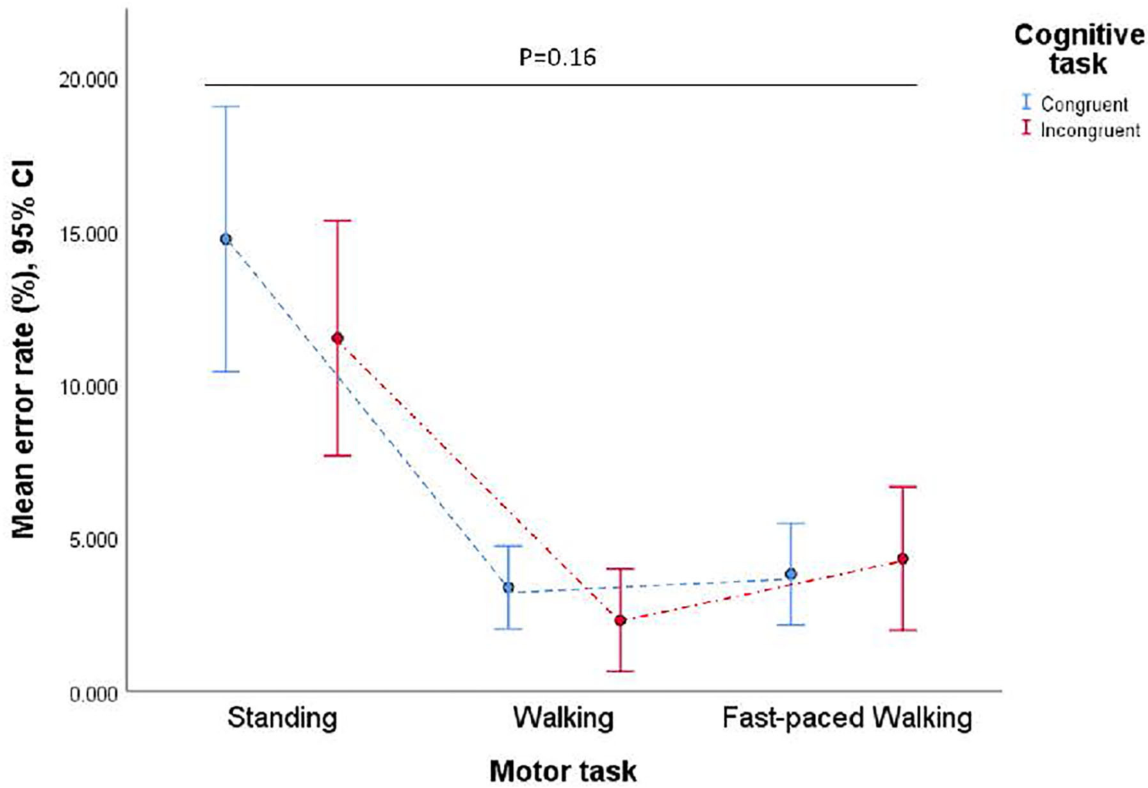

FIGURE 5 | Means error rate for the congruent and the incongruent task in all VR dual-tasking conditions. Figure showing no interaction between motor task and cognitive task on error rate.

rates. Finally, the VR treadmill has a unique potential to create VR conditions with various gait speeds and different levels of cognitive engagement.

Feasibility of the VR Condition

The researchers intended to develop replicable conditions to examine the effects of exercise intensity and mode on cognitive performance. Once established, this would permit the examination of cognitive performance before, during, and after exercise. The study has value because a prominent health risk factor is physical inactivity or sedentary behaviors, which have risen steadily. Our primary objective was to determine the feasibility of the varying dual-task conditions using the VR treadmill. The researchers measured each individual's physiological cost to confirm the reliability to consistently produce the expected energy demands (Li et al., 2005; Schaefer, 2014). Li et al. (2005) had previously identified several limitations of dual-tasks assessments: (a) the laboratory environment should be as close as possible to real-world settings; (b) performance of each task and their interrelations should be compared for all tasks involved; and (c) task difficulties should be systematically varied to challenge individuals at appropriate levels. The researchers asked the participants to respond as fast as possible to a stimulus representing a visual distraction during the presented VR conditions parallel to real-world experience. Our study used a 180° degree VR projection screen and generated six different conditions with varying cognitive and motor difficulties. General dual-tasking studies typically used disconnected cognitive tasks. However, activities people perform in the real world far more commonly involve balancing tasks that integrate with their movements (e.g., using a cell phone while walking, etc.). The present study used the VR system to measure the cognitive task integrated with the participants' movement responses. Thus, this extends the literature regarding the measurement of combined physiological and behavioral effects to more ecologically relevant scenarios.

Exercise Intensity Validation Through Physiological Responses

The majority of treadmill walking studies confirmed that speed was the most common reported gait outcome measure, reflecting its practical simplicity and clinical usefulness (Al-Yahya et al., 2011). This study used gait speed to control three different exercise intensities. This generated a significant difference between each condition on the HR and step counts. The researchers assumed that PWS and fast-paced walking conditions would generate light to moderate intensity of exercise and that this process could be verified through accelerometer measures because the use of steps/min data through accelerometry has become a promising method to validate exercise intensity categories (i.e., light, moderate, high) in young adults (Treuth et al., 2004). The researchers experienced some difficulties using the accelerometers to establish the thresholds for vigorous activity. However, the average step counts of the PWS walking condition (116.13 steps/minute), and fast-paced walking condition (129.38 steps/minute), did align with the light to moderate activity intensity categories established by Tudor-Locke et al. (2005).

Polar HR data was used to determine the intensity of exercise between conditions, because it is linearly related to oxygen uptake for dynamic activities (Freedson and Miller, 2000; Strath et al., 2002), which is the standard measure of energy expenditure during non-maximal or stress test treadmill studies. HR during standing condition was significantly higher than resting HR [$t(28) = 9.93$, $p < 0.01$], which implied that the standing condition itself ($M = 85.71$, $SD = 17.35$) has a short bout of light-intensity exercise with 25–40% heart rate reserve (HRR) by the method of Karvonen formula (Karvonen and Vuorimaa, 1988). Also, the PWS condition trained at 40–55% of HRR, between light and moderate-intensity exercise categories. Comparing step counts and HR indicated that PWS condition showed the light to moderate intensity of exercise, which might facilitate cognitive processing more than standing (light-level) and fast-paced walking (moderate-level) conditions under the dual-task paradigm. Given the different performance responses, our findings are supported by the inverted U-shape of arousal. Further, in pre/post designed experiments with individuals who participate in moderate to vigorous acute bouts of physical activity, reaction time is lower post-exercise than pre-exercise (Hogan et al., 2013). Although these effects are not as strong as those among older adults, they are still statistically significant and clinically relevant, as faster responders can process information more rapidly. Specific to dual-tasking contexts, physical activity could lead to enhanced processing when expedited reallocation of attentional resources is needed, perhaps even required for survival (e.g., avoid an oncoming car).

Behavioral Response of Walking and Fast-Paced Walking

Given the known association between gait and cognition, the researchers hypothesized that performance would deteriorate when the participants walked. The hypothesis did not hold, and instead, the opposite occurred, with walking and fast-paced walking having better reaction time and error rate than the standing condition. Despite the starting point being randomly assigned, the increases in behavioral responses and cognitive performance were likely because these healthy young participants were at their cognitive peak and could shift their attention from one task to another without a detectable decline in performance. Further, performance could have improved because walking is a rote task, and attention was shifted to the cognitive task. Among 40 young active and sedentary adults (M age = 21.4 years of age), task-switching performance, measured as reaction time, was superior among those who were regularly active (Kamijo and Takeda, 2010). The male participants in this study were classified as healthy, while the females were classified as overweight. However, on the health questionnaire, 85% of the participants stated that they were meeting the national physical activity guidelines of 150 min of moderate to vigorous physical activity each week. Although beyond the scope of this study, health risk factors could have influenced the results.

Moreover, the cognitive tasks were based on the Go/No-Go paradigm and likely were too simple for the educated participants, and therefore what they experienced was an environment of mutual facilitation (Plummer et al., 2013). In this environment, all congruent/incongruent tasks provided both visual and auditory feedback, so when an error was made, the participant could learn from their mistake and adapt their performance. Since there was no significant order effect among the conditions, the researchers concluded that the condition's integrity was preserved. The participants in this study have potentially experienced gaming and VR environments in daily living and overcame the potential for increased risk for variability associated with dual-task interference (Chopra et al., 2018) because of their ability to shift their attention from one stimulus to the next. Future studies should include VO_2 max testing as an objective measure of fitness. Further, participants should be screened for previous VR and gaming experiences to account for possible historical factors that may have influenced internal validity.

Behavioral Responses of Reaction Time and Error Rate

Previous dual-task studies that combined exercise with cognitive test conditions frequently report degraded cognitive performance, reflecting slower reaction time (Plummer and Eskes, 2015; Herold et al., 2018). However, this study revealed the facilitation of participants' cognitive performance during treadmill walking rather than standing.

Several possibilities can be interpreted from these results. First, treadmill walking is usually highly automatized and does not necessarily lead to performance decrements in cognitive processing (Lövdén et al., 2008; Schaefer et al., 2010). This result is supported by other dual-task studies suggesting that when the pace on the treadmill is preferred, it does not interfere with the attention demand of motor tasks (Bloem et al., 2001; Tomporowski and Audiffren, 2014). Further, treadmill walking did not include any perturbation, which can happen in real-life walking. Patel et al. (2014) investigated the effect of different cognitive tasks and gait speeds on cognitive-motor interference of dual-task walking in young adults. As they remarked, PWS on the treadmill can prioritize complex cognitive tasks requiring higher attentional and processing resources over walking. Rather than sitting and slow-speed walking, PWS walking showed the most effective way to perform the cognitive task under the dual-task structure.

Second, it is possible PWS walking itself might lead to a better performance of the cognitive task. Our study results support the previous studies that preferred walking gait speed during dual-tasking conditions has beneficial effects on cognitive performance (Beauchet et al., 2005; Yogev-Seligmann et al., 2010;

Al-Yahya et al., 2011). The cognitive improvement during dual-task walking is consistent with the "inverted-U shape theory" for cognitive processing (Yerkes and Dodson, 1908; Anderson, 1990). The inverted-U theory assumes that when physical arousal increases, performance is predicted to improve up to a maximum point and then to deteriorate with further increases in physical arousal. For example, Kamijo et al. (2007) investigated the effect of exercise intensity and task difficulty on cognitive processing using the P3 component of event-related brain potential. The P3 amplitude increased across task conditions following light and moderate cycling, but not during hard cycling, relative to baseline. The authors concluded that P3 amplitude might change in an inverted U-shape fashion due to acute exercise intensity. This inverted-U theory suggests that the optimal arousal level might depend on the difficulty of the given task. More specifically, if a task is complex in a dual-task paradigm, moderate cognitive and physical arousal levels might result in better performance.

In contrast, high/low levels of arousal will result in a deterioration of performance. If, however, the task is simple, it might require higher levels of arousal for optimal performance to be exhibited (Kamijo et al., 2004; Pesce, 2012). Schaefer et al. (2010) reported similar results with a young adult age group that participants' working memory performance was facilitated when walking at the preferred speed, but not at a fixed slower pace. They concluded that the interaction of walking and cognitive performance is influenced by sharing resources under the dual-task paradigm, and an exercise-induced activation of resources may cause that performance improvement in the cognitive task. In the present experiment, participants' reaction times and error rates changed appreciably when they walked at their PWS, compared to standing. Even though fast-paced walking did not show a significant difference in performance, we believe this was because the treadmill speed was not fast enough to deteriorate the attentional resources.

Adapted Congruent/Incongruent Task Comparison Under the Dual-Task Paradigm

Different results can be found in cognition-exercise studies depending on which cognitive task is applied in the dual-task paradigm. Our study utilized an adapted congruent/incongruent task of the Go/No-Go paradigm, which elicits inhibition control. Average scores of the congruent tasks during treadmill exercise showed faster reaction time than average incongruent tasks, but there was no difference in the error rate. Given that result, the incongruent task required more cognitive processing time than the congruent task, but there was no difference between the tests on the error rate. This finding suggests that they needed more time to plan the response movement during the incongruent task, but they could still execute those movements appropriately. McMorris and Hale (2012) and McMorris (2015) obtained a similar result in which processing speed may facilitate exercise, but not on the error rate factor. Accuracy improvement took place only when the timing of testing was post-exercise, not during exercise.

Strengths and Limitations

The present study has several strengths and limitations. Among the strengths are an attempt to develop an ecologically valid VR condition for testing exercise dose-response effects on cognitive performance. Also, there was a direct comparison of performance by condition within each participant. Finally, the use of VR to create a realistic simulation of the natural conditions within a controlled lab setting was novel and opened the door for new ways to understand the relationship between exercise and cognitive performance. As for the limitations, first, participant's standing conditions may have been a disadvantage for the reaction time because the condition did not result in a natural arm swing. Although all stimuli were blocked and displayed for the same duration on the screen, future studies should address this limitation by using markers to measure work and distance from the standing point and stimuli. Second, dual-task interference or facilitation to support the inverted-U theory may depend on the cognitive test selected. Our study only used adapted congruent/incongruent tasks for the cognitive assessment, but future research should encompass several cognitive performance tasks with variable demands to better understand this relationship. Third, behavioral responses were classified and dichotomously coded as correct or incorrect, and as such, we do not have a full understanding of why a participant may not have elected to respond to a displayed stimulus.

CONCLUSION

Motor-cognitive dual-tasking limited attentional resources in various settings. Our study confirmed that dual-task-related changes in gait speed are sensitive to the performance and could reflect the exercise intensity differences with HR and step counts responses. PWS condition generated lower reaction time and error rate than standing condition, which implicated that self-paced walking can increase blood flow in the prefrontal cortex. Cognitive demanding differentiation while treadmill exercises impact the reaction time, but not the error rate within these conditions. This result implied that speed of processing during congruent task while the VR treadmill condition was faster than incongruent task while VR treadmill condition, but not on the cognitive performance accuracy. Future studies need to identify the brain mechanisms underlying arousal-induced resource activation. Therefore, physiological data (e.g., blood draw) or brain data (e.g., fNIR) can incorporate with advanced technology such as the VR treadmill. Although the present study only investigated young adults' age groups, children and older adults, or humans acquiring a new motor skill might be a relevant group comparison study.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Texas at Austin. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

YJ: conceptualization, planning, data collection, data analysis, and writing of the manuscript. JD: conceptualization, planning, writing of the manuscript, supporting proofreading, and supporting data analysis. PC: protocol development, data collection, and data analysis. BB: data collection, data analysis, and writing of the manuscript. DC: conceptualization, planning, and supporting proofreading. All authors: contributed to the article and approved the submitted version.

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