NONLINEAR PEDAGOGY IN PHYSICAL EDUCATION TEACHING: PROMOTING EXECUTIVE FUNCTIONS DEVELOPMENT

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ABSTRACT

Educational Neuroscience highlights embodied learning as a key driver of children's cognitive and psychophysical development, reinforcing the role of Physical Education (PE) in promoting health and well-being throughout developmental age. Grounded in ecological-dynamical theory, Nonlinear Pedagogy (NLP) promotes adaptive processes through task and environmental constraints, supporting active lifestyles and flexible, situation-specific behaviours in childhood. This study examined the effects of an NLP-based PE intervention on attention and visual processing speed in primary school children (N = 165; mean age = 7.21 ± 0.93), compared to traditional instruction over 16 weeks. Results, collected through Witty SEM technology, allowed an objective assessment of cognitive performance, suggesting that NLP-oriented environments can enhance attention and decision-making efficiency, supporting Physical Education contexts that promote cognitive development in primary school age children.

KEYWORDS

Cognitive Development; Ecological Dynamic Approach; Nonlinear Pedagogy; Physical Education; Primary School Children.

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[1] Author contribution: E.P.: study design, methodology, results, and discussion; P.F. and C.M.: introduction and instruments; F.C.: data curation and figures; D.M.: data curation and statistical analysis; C.D.: introduction, conclusion, and overall study supervision.

1. Introduction

Over the past two decades, increasing attention has been devoted to understanding how discoveries in neuroscience can inform educational research and practice. This interest has led to the development of educational neuroscience, an interdisciplinary field that combines knowledge from neuroscience, psychology, and education to investigate the biological mechanisms underlying learning and to identify teaching approaches that can effectively support children's cognitive, emotional, and social development (Ansari et al., 2012; Howard-Jones, 2014). Within this framework, learning is viewed as a dynamic process through which experience continuously modifies the structure and functioning of neural circuits. Rather than the simple accumulation of information, learning reflects the brain's capacity to adapt to environmental demands by reorganizing neural networks. Throughout childhood, educational experiences play a key role in guiding brain development by reinforcing functional connections and promoting adaptive neural plasticity in response to meaningful environmental interactions (Immordino-Yang & Damasio, 2007; Kolb & Gibb, 2011).

Developmental age is characterized by high neuroplasticity, enabling continuous adaptation of brain structure and function in response to experience. Processes such as synapse formation and elimination, myelination, and experience-dependent neural remodelling are strongly shaped by interactions with the physical and social environment. Movement-based experiences, active exploration, and play provide rich multisensory input that supports these mechanisms, contributing not only to motor development but also to the maturation of neural systems underlying perception, cognition, and behaviour (Diamond, 2020). Because childhood represents a critical window for brain development, the quality of environmental experiences becomes particularly relevant. Physical activity offers repeated opportunities to

perceive, act, make decisions, and adapt behaviour to changing constraints. Through continuous perception–action coupling, motor skill acquisition supports executive functions, attentional control, working memory, cognitive flexibility, and self-regulation, all closely linked to learning and academic achievement (Best & Miller, 2010; Diamond, 2015).

Recent literature has increasingly highlighted the close relationship between motor activity and cognitive development, demonstrating that enriched and cognitively engaging movement experiences can positively influence executive functioning, attention, and memory (Matrisciano et al., 2025; Song et al., 2022; Srinivas et al., 2021; Zhou & Tolmie, 2024). Physical activities characterised by variability, problem-solving, and environmental interaction appear especially effective in promoting cognitive outcomes during childhood (Tomporowski et al., 2008; Van der Fels et al., 2015). Within this perspective, Nonlinear Pedagogy (NLP) has emerged as a relevant educational framework for physical education and child development. Rooted in the ecological dynamics approach, NLP differs from traditional linear models based on repetition and prescriptive instruction by emphasising exploratory learning, adaptability, and learner autonomy (Chow et al., 2007; Correia et al., 2019; Komar et al., 2022).

Learning is considered a self-organising process arising from the interaction among individual, task, and environmental constraints. Through the manipulation of these constraints, children are encouraged to explore multiple movement solutions, adapt their behaviour, and actively construct knowledge (Button et al., 2021; Chow, 2013; Davids et al., 2013). Teachers play an active role in continuously adapting learning environments by modifying task and environmental constraints in response to learners' behaviours. Evidence supports the effectiveness of NLP-based interventions in school contexts, showing improvements in motor competence, creativity, physical literacy, and

cognitive functioning when children engage in variable and exploratory movement tasks rather than repetitive instruction (Cooke et al., 2022; NaeimAbadi & Bagheri, 2024; Yang et al., 2025).

Importantly, NLP aligns strongly with the development of executive functions because children are continuously required to make decisions, inhibit ineffective responses, adapt to changing task demands, and regulate their behaviour in dynamic contexts (Kaloka et al., 2024; Rudd et al., 2019). Such environments integrate motor, cognitive, emotional, and social demands, fostering self-regulation, attention, and flexible thinking. Evidence also indicates that cognitively challenging, emotionally engaging, and socially interactive movement experiences are particularly effective for neurocognitive development during childhood (Diamond, 2013; Diamond & Lee, 2011; Pesce & Ben-Soussan, 2016).

From an ecological-dynamic perspective, motor behaviour emerges through the continuous interaction between the individual, the task, and the environment (Newell, 1986). Learning is therefore adaptive, contextual, and non-linear rather than prescriptive. Educational effectiveness depends less on fixed instructional sequences and more on continuous adjustment of learning constraints to support learner–environment interactions. NLP operationalizes these principles through representative learning design, affordances, and game-based activities that promote exploration and autonomy (Chow et al., 2020, 2021; Chow & Atencio, 2014). By creating variable and meaningful movement experiences, this approach may support not only motor competence but also higher-order cognitive processes in early school age (Bortoli & Robazza, 2016; Davids et al., 2003; Monacis et al., 2022; Sannicandro & Colella, 2023).

Although correct-response outcomes provide important evidence of cognitive performance, accuracy alone cannot indicate how briefly relevant visual information may be presented while a child continues to perform the task. Accuracy and the adaptive stimulus-time threshold therefore represent conceptually distinct, potentially complementary dimensions: the former reflects response success, whereas the latter reflects the exposure duration reached within the device's adaptive procedure. Two children may achieve similar correct-response counts while requiring different exposure durations; conversely, a lower threshold does not establish greater accuracy. A previous analysis of this cohort reported intervention-related changes in correct-response counts across the Divided Attention and Hawk Eye tasks (Pugliese et al., 2025). The adaptive stimulus-time thresholds were not reported or analysed in that article. The present research question is therefore conceptually distinct: it examines performance under progressively shorter stimulus exposure, information that cannot be inferred from accuracy alone. This analysis was conducted retrospectively as an exploratory secondary analysis and is not presented as a prespecified confirmatory analysis.

Accordingly, this study examined whether a 16-week school-based physical education intervention grounded in Nonlinear Pedagogy and ecological dynamics was associated with lower adaptive stimulus-time thresholds in primary-school children. The intervention retained its original emphasis on exploration, variability, learner autonomy, and continuous adaptation of task constraints. The primary outcomes for this exploratory analysis were the pre- to post-intervention adaptive stimulus-time thresholds from two levels of the Divided Attention task and two levels of the Hawk Eye task. It was expected that, after adjustment for the corresponding baseline threshold, children in the

experimental group would demonstrate lower post-test thresholds than children following the traditional curriculum; this directional expectation was interpreted as exploratory rather than confirmatory.

2. Materials & Methods

A quasi-experimental between-subject design was adopted involving 165 first-grade primary school children.

Participants attended two weekly physical education lessons, as confirmed by school records. Eight classes were randomly assigned to either an experimental group or a control. Due to the school-based nature of the intervention, neither allocation concealment nor teacher blinding was feasible.

The experimental group participated in a 16-week intervention integrated into regular physical education classes, while the control group followed the standard curriculum. Assessments were conducted before (T1) and after the intervention period (T2).

2.1 Participants

The study involved 165 first-grade children from eight classes of a primary school in southern Italy. Based on class membership, participants were assigned to an experimental group (EG; n = 98) or a control group (CG; n = 67), in line with school organisational constraints. Only the EG participated in the intervention programme. The intervention was conducted during regular physical education lessons by a Sports Science graduate under teacher supervision and was aligned with the Italian National Curriculum Guidelines (MIUR, 2012). These guidelines promote motor skill development, body awareness, adaptation to environmental demands, and the integration of cognitive, motor, and social learning processes. The EG followed a Nonlinear Pedagogy-based programme centred on exploratory, variable, and game-based

activities, whereas the CG continued the standard curriculum using a traditional linear approach characterised by repetitive and prescriptive motor exercise (MIUR, 2012, 2016). Both groups were supervised by qualified Sports Science graduates and classroom teachers.

2.2 Intervention

The programme was integrated in the regular physical education curriculum and lasted 16 weeks, comprising two 50-minute sessions per week (32 lessons). It was designed according to Nonlinear Pedagogy principles, emphasizing exploration, variability, adaptability, and active engagement. Implementation fidelity was monitored through systematic collection of attendance records, teacher reports, and structured observation checklists. Monitoring focused on adherence to key NLP principles, including variable practice, constraint manipulation, and opportunities for exploration. All sessions were delivered as planned, attendance remained consistently high, and no adverse events occurred. Sessions were conducted by the class teacher, physical education specialists, and members of the research team.

The intervention promoted variable and enriched movement experiences designed to simultaneously engage motor, cognitive, emotional, and social processes. Activities avoided repetitive technical exercises, instead encouraging learners to explore functional movement solutions under continuously changing task and environmental constraints, integrating perception, decision-making, and action in game-based contexts.

Each session followed a three-phase structure: an activation phase, a cognitively demanding motor phase, and a concluding reflective phase. Table 1 summarizes the session structure.

Table 1. *Session Structure*

Phase	Duration	Main Focus	Specific Objectives
1	10-15 min	Introduction of the first game; playful, engaging physical activation.	- Stimulate quick decision-making - Start the lesson in an enjoyable way (team, pair, or individual games). - Acquire/improve fundamental motor skills, coordinative and conditional components, and gross motor abilities
2	30-35 min	Cognitive–motor exercises with a gradual progression of difficulty (aligned with Nonlinear Pedagogy principles).	- Stimulate selective/divided attention, inhibitory control, visual discrimination, decision-making, self-organization, and visual processing speed. - Encourage interaction through cooperative or competitive formats, requiring children to constantly adapt to tasks and roles. - emotional and social development through shared experiences
3	5 min	Reflection on the experience (collective debriefing) and restoring psychophysical balance.	- Gather feedback (level of enjoyment, favourite aspects, suggested modifications). - Help children recover physically and mentally to prepare for the classroom setting.

Consistent with the principles of Nonlinear Pedagogy, the intervention was not conceived as a rigid sequence of exercises but was designed around predefined pedagogical objectives and constraints. The selection and progression of activities were continuously adapted to participants' characteristics and the evolving learning process. To ensure methodological transparency, Table 2 provides an illustrative overview of the intervention structure, pedagogical principles, and instructional procedures.

Table 2. *Illustrative Structure of the Intervention*

	Activities proposed in phase 2	Description	Variant	Motor Objective	Cognitive Objective	Integrated NLP principle
1	**Numeri di partenza**	Every child has a number. At the signal, those who hear their number called leave to perform a motor task (e.g. jumping obstacles, running, etc.)	Children must also remember and call a second number at the end of the course, involving a friend	Stimulate motor skills and abilities: balance (static and dynamic), coordination, adaptation, endurance, speed	Selective attention and working memory	*Functional variability; Information–movement coupling; Manipulation of constraints* (The task is built in continuous interaction between peers, in a dynamic context)
2	**Tris con percorso**	Two teams compete in a race in turn to complete a tic-tac-toe with hoops or cones, after a short motor path	Change the route each time (hops, animal gaits, balance)	Stimulate motor skills and abilities: balance (static and dynamic), coordination, adaptation, strength, endurance, speed, basic motor patterns (gaits in quadrumania)	Strategic planning and hand-eye coordination	*Functional variability; Information–movement coupling; Manipulation of constraints* (different ways to achieve the same goal: based on the motor path, independently choose how to adapt to the problem posed)

2.3 Tools

Parents provided written informed consent and completed a background questionnaire adapted from the Physical Activity Questionnaire for Children (PDPAR) (Weston et al., 1997). Age and sex were used to describe the cohort consistently with the previous report of this study sample (Pugliese et al., 2025).

Cognitive performance was assessed using the Witty SEM system (BrainHQ | Microgate, n.d.), a computerised hardware-software platform that integrates visual stimulus presentation with motor responses. Wireless LED pods displayed colours, numbers, symbols, or directional cues, while proximity and touch sensors registered responses produced through hand or foot movements. This configuration enabled movement-based assessment of attention, visuomotor coordination, visual processing, and decision-making. Two protocols were administered (Executive functions training | Microgate, n.d.). Their task structure is described in the manufacturer manual (Microgate, 2024). The Divided Attention task required a yes/no judgement about paired visual stimuli presented across four pods. The Hawk Eye task required identifying the location of one discrepant stimulus among several briefly presented stimuli. Each protocol was completed at two predefined task-difficulty levels, producing four outcomes: Divided Attention Level 1 (DA1), Divided Attention Level 2 (DA2), Hawk Eye Level 1 (HE1), and Hawk Eye Level 2 (HE2). These labels denote preset task difficulty and are distinct from the adaptive stimulus-time threshold recorded for each task (Microgate, 2024).

The Witty SEM system automatically recorded two complementary aspects of performance for each task: accuracy, operationalised as the number of correct responses, and a device-exported adaptive stimulus-time value. The correct-response outcomes were analysed and reported in the previous publication from this cohort (Pugliese et al., 2025). In the present manuscript, the exported

value was operationally defined as the adaptive stimulus-time threshold and constituted the outcome of this secondary analysis. According to the manufacturer documentation, the tasks begin from a configurable stimulus-exposure duration, normally 1.0 s, which is adjusted throughout the task according to performance. Successful responses lead to a shorter subsequent exposure, whereas difficulty responding within the available interval leads to a longer exposure; the duration can decrease towards a configurable minimum, set by default at 0.032 s, over a predefined number of repetitions (Microgate, 2024). For each participant, one adaptive stimulus-time threshold was available for DA1, DA2, HE1, and HE2 at both T1 and T2, giving eight threshold values. Trial-by-trial adjustments were not modelled. A lower threshold indicates that the child maintained task performance with a shorter stimulus-exposure duration and should not be interpreted as a conventional reaction-time measure.

3. Statistical Analysis

Analyses were conducted in Python 3.12.13 using pandas 2.2.3, NumPy 2.3.5, and SciPy 1.17.0. All 165 participants had complete data for the eight adaptive stimulus-time threshold variables (four tasks assessed at two time points), producing 1,320 threshold measurements. The thresholds occurred at discrete, geometrically spaced exposure-duration levels and were therefore log2-transformed for analysis. Descriptive statistics were back-transformed and presented as geometric means in seconds with 95% confidence intervals (Bland & Altman, 1996). A separate baseline-adjusted linear model was fitted for each task, with the log2-transformed post-test threshold as the dependent variable, group as the predictor of interest (0 = control; 1 = experimental), and the corresponding log2-transformed pre-test threshold as a covariate. HC3 heteroskedasticity-consistent standard errors were used. The group coefficient

was back-transformed as 2^β and reported as an adjusted threshold ratio; ratios below 1 indicated a lower post-test threshold in the experimental group after adjustment for baseline. The percentage by which the experimental-group threshold was lower was calculated as (1 - adjusted threshold ratio) x 100. To control the false-discovery rate across the four primary outcomes, p values were adjusted using the Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995). Two-sided unadjusted p values, FDR-adjusted p values (pFDR), adjusted threshold ratios, and 95% confidence intervals are reported. Statistical significance was set at pFDR < .05.

4. Results

Participant adherence to the study protocol exceeded 95% in both groups. No adverse events, injuries, safety-related issues, or study discontinuations were recorded during the 16-week intervention. The final sample comprised 165 children: 67 in the control group and 98 in the experimental group. The control group included 28 boys (42%) and 39 girls (58%), with a mean age of 7.28 years (SD = 1.02); the experimental group included 44 boys (45%) and 54 girls (55%), with a mean age of 7.31 years (SD = 0.94).

Participant characteristics are summarised in Table 3. Age (p = .842) and sex distribution (p = .611) did not differ significantly between groups.

The analytical sample was complete for all four adaptive stimulus-time thresholds at T1 and T2. Baseline threshold distributions were addressed directly by including the corresponding pre-test threshold in each outcome-specific model.

Table 3. *Participant characteristics reported for the study cohort*

Characteristic	Control group	Experimental group	p
n	67	98	-
Age, years (M ± SD)	7.28 ± 1.02	7.31 ± 0.94	.842
Boys, n (%)	28 (42%)	44 (45%)	.611
Girls, n (%)	39 (58%)	54 (55%)	

Table 4 presents the geometric mean adaptive stimulus-time thresholds at T1 and T2 and the baseline-adjusted group effects. All four adjusted ratios were below 1, and every 95% confidence interval excluded 1. The intervention effect remained statistically significant for each outcome after FDR correction (all pFDR < .001).

Table 4. *Adaptive stimulus-time thresholds and baseline-adjusted group effects*

Task	CG T1 GM (s)	CG T2 GM (s)	EG T1 GM (s)	EG T2 GM (s)	Adjusted EG/CG ratio (95% CI)	p	pFDR
DA1	1.574	1.097	1.626	0.723	0.658 (0.559-0.773)	< .001	< .001
DA2	3.609	1.915	3.067	1.428	0.754 (0.641-0.887)	< .001	< .001
HE1	0.054	0.070	0.049	0.038	0.537 (0.439-0.657)	< .001	< .001
HE2	0.086	0.114	0.062	0.034	0.293 (0.244-0.353)	< .001	< .001

For DA1, both groups showed lower thresholds at post-test, but the reduction was greater in the experimental group. After adjustment for baseline, the experimental group's threshold was 34.2% lower than the control group's threshold (adjusted ratio = 0.658, 95% CI [0.559, 0.773], pFDR < .001). A similar pattern was observed for DA2: the experimental group had a 24.6% lower adjusted post-test threshold (adjusted ratio = 0.754, 95% CI [0.641, 0.887], pFDR < .001).

The group difference was larger for the Hawk Eye outcomes. For HE1, the control-group geometric mean increased from 0.054 s to 0.070 s, whereas the experimental-group mean decreased from 0.049 s to 0.038 s. The adjusted experimental-group threshold was 46.3% lower than the control-group threshold (adjusted ratio = 0.537, 95% CI [0.439, 0.657], pFDR < .001).

HE2 showed the largest adjusted effect. The control-group geometric mean increased from 0.086 s at T1 to 0.114 s at T2, while the experimental-group mean decreased from 0.062 s to 0.034 s. Following baseline adjustment, the experimental group had a 70.7% lower post-test threshold (adjusted ratio = 0.293, 95% CI [0.244, 0.353], pFDR < .001). Overall, the results consistently favoured the experimental condition, with the most pronounced differences in the Hawk Eye tasks (Figure 1).

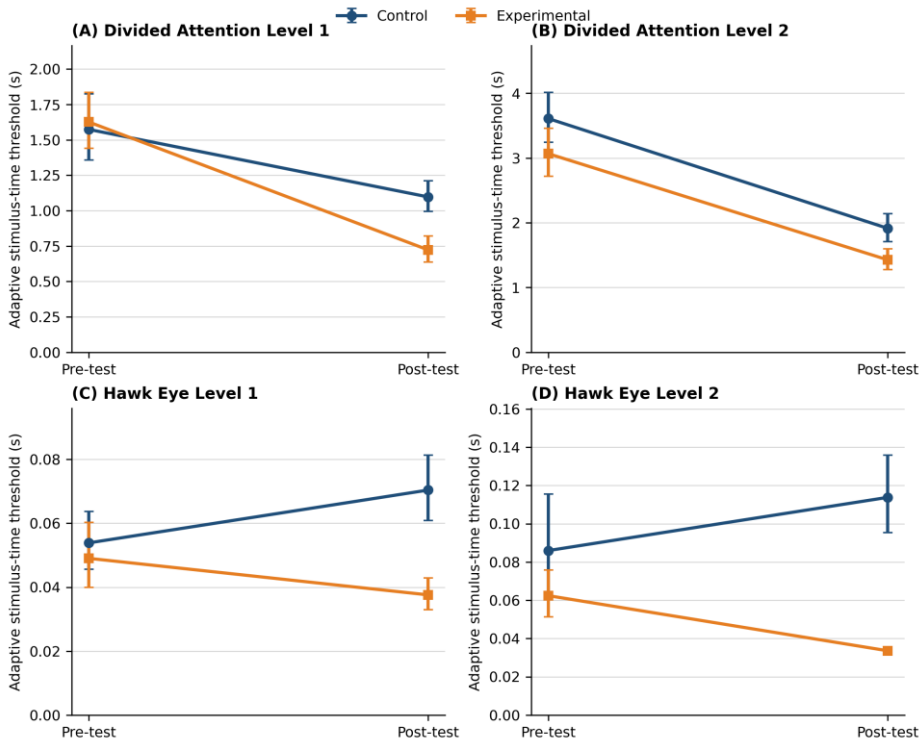


Figure 1. *Geometric mean adaptive stimulus-time thresholds for (A) Divided Attention Level 1, (B) Divided Attention Level 2, (C) Hawk Eye Level 1, and (D) Hawk Eye Level 2. Error bars represent 95% confidence intervals. Lower values indicate shorter stimulus exposure.*

5. Discussion

This exploratory, retrospective secondary analysis found that the Nonlinear Pedagogy (NLP)-based intervention was associated with lower adaptive stimulus-time thresholds across all four tasks. After adjustment for the corresponding baseline threshold, differences favoured the experimental group for both levels of Divided Attention and Hawk Eye, with the largest effects observed in the Hawk Eye tasks. The intervention also showed high adherence and no adverse events, supporting its feasibility within regular primary-school physical education. These results concern performance under progressively shorter stimulus exposure, a temporal dimension that is distinct from the correct-response outcomes reported for these tasks (Pugliese et al., 2025).

In the Divided Attention tasks, adaptive stimulus-time thresholds decreased in both groups, but baseline-adjusted post-test values were lower in the experimental group. The Hawk Eye pattern was more distinctive: thresholds decreased in the experimental group but increased in the control group, producing the largest adjusted differences, particularly at Level 2. Because the adaptive stimulus-time threshold is operationally defined as the device-exported value reached within the adaptive procedure, these findings indicate that the experimental group performed the tasks at shorter device-controlled exposure durations. They should not be interpreted as conventional single-trial reaction-time effects or as direct evidence of a specific cognitive mechanism.

The findings are consistent with evidence that movement-based interventions are more likely to engage cognitive processes when their motor demands are combined with changing rules, decision-making, perceptual challenges, and the need to adapt responses. Such cognitively enriched movement experiences have been associated with attention and executive-control outcomes in children (Cabral et al., 2025; D'Anna, Basadonne, et al., 2025; Forte et al., 2025;

Lovecchio & Pittaluga, 2024; Pugliese et al., 2025). The present results extend this educational perspective to performance under adaptive visual-exposure demands, while remaining specific to the tasks and measurement procedure used.

The educational relevance of this pattern lies in the setting in which it emerged. The intervention was delivered through school physical education rather than as a separate computerised cognitive-training programme. Physical education can provide repeated opportunities for children to perceive information, make decisions, coordinate actions, solve movement problems, and regulate behaviour with peers under changing task demands. Accordingly, its contribution to children's development may depend not only on the amount of movement performed, but also on how movement experiences are designed and taught. This view is consistent with research emphasising cognitively engaging physical activity and pedagogies that connect movement learning with executive function and self-regulation (Cooke et al., 2022; Rudd et al., 2019; Song et al., 2022). It does not imply that physical education automatically produces general cognitive gains; rather, it identifies lesson design and learner engagement as educationally relevant features.

Nonlinear Pedagogy provides a specific account of how such learning conditions may be created. Rather than reproducing a fixed sequence of exercises, the teacher adjusted task difficulty, space, rules, equipment, and social interaction in response to learners' behaviours and emerging needs. Fidelity in this context therefore concerns the coherent application of shared pedagogical principles while the task constraints used to realise those principles remain adaptable. This adaptive fidelity positions the teacher as a designer of learning ecologies who shapes affordances and opportunities for exploration, problem-solving, and self-organisation rather than transmitting a single prescribed movement solution (Chow et al., 2011; Renshaw et al., 2019).

The pedagogical interpretation is therefore that outcomes may depend less on reproducing isolated activities and more on the quality, coherence, and responsiveness of constraint manipulation across the learning process.

From a theoretical perspective, these adaptive learning environments may support flexible regulation of perception and action. Repeated engagement with variable informational and task constraints requires children to detect relevant cues, redirect attention, select responses, and reorganise action as circumstances change. Within Ecological Dynamics, learning emerges through interactions among learner, task, and environment and is expressed through increasingly functional perception–action relations, attunement to information, and use of affordances (Araújo et al., 2019; Coppola et al., 2024; Pugliese et al., 2023; Seifert et al., 2025). Variability is consequently treated as a functional property of learning rather than as noise to be eliminated. The lower adaptive stimulus-time thresholds may be compatible with greater flexibility under changing perceptual and attentional demands, although the present outcome cannot identify the underlying mechanism and this interpretation remains provisional.

For physical education practice, the implication is not to reproduce the individual activities used in this intervention as a standardised protocol. Instead, teachers may create developmentally appropriate problems that preserve the purpose of a task while varying the information, space, rules, equipment, or interpersonal relations available to each learner. Observation and responsive adjustment are central: constraints should make relevant information detectable, invite more than one functional solution, and maintain a level of challenge that supports participation without removing uncertainty. In this way, motor learning and cognitive engagement are integrated within meaningful movement experiences rather than treated as competing curriculum goals (Chow & Atencio, 2014; Chow et al., 2021; Correia et al., 2019).

From a methodological standpoint, the Witty SEM system provided an adaptive stimulus-time threshold that conventional accuracy scores do not capture. The manufacturer documentation describes the adaptive shortening or lengthening of stimulus exposure and the configurable start, minimum, and repetition settings (Microgate, 2024). The statistical models used the single adaptive stimulus-time threshold exported by the device for each task and assessment point; trial-by-trial adjustments were not modelled. Accordingly, the findings identify group differences in the exposure-duration threshold reached within the adaptive procedure and should not be interpreted as differences in conventional reaction time. Future research should preregister adaptive stimulus-time thresholds as outcomes, archive complete trial-level adaptive histories and device configurations, and establish their test–retest reliability, convergent validity, and relationship with accuracy. Larger studies should also examine whether changes are retained and transferred to other educational or motor contexts. From a pedagogical perspective, research should move beyond identifying an optimal exercise protocol to document how teachers observe learners, select and modify constraints, and maintain appropriate challenge over time. Linking these teaching processes to motor, cognitive, motivational, and participation outcomes would clarify which features of nonlinear learning environments are most educationally consequential.

6. Conclusion

This study found that a 16-week school-based physical education intervention grounded in Nonlinear Pedagogy was associated with lower adaptive stimulus-time thresholds in Divided Attention and Hawk Eye tasks. After baseline adjustment, children in the experimental group performed under shorter stimulus-exposure durations than children in the control group, with the largest differences in the Hawk Eye tasks. These findings support a task-specific

interpretation concerning adaptive temporal performance; they do not demonstrate a general improvement in executive functioning or a change in conventional reaction time.

In educational terms, the findings reinforce the potential of physical education to serve as more than a setting for accumulating physical activity or practising predetermined motor techniques. When lessons require children to explore, perceive relevant information, make decisions, solve movement problems, and coordinate with others, motor and cognitive demands can be integrated within the same learning experience. This is especially relevant in primary school, where physical education offers regular, inclusive opportunities to engage children through embodied and socially meaningful tasks. The educational contribution therefore lies not in adding a separate cognitive-training component to physical education, but in enriching the design of movement learning itself (Rudd et al., 2019; Song et al., 2022).

Nonlinear Pedagogy provides the organising framework for this approach. Learning is shaped through interactions among individual, task, and environmental constraints, while the teacher designs and continually adapts the learning environment in response to children's actions and needs. Manipulating space, rules, equipment, task difficulty, and social relations can preserve the educational intention of a lesson while allowing multiple functional solutions to emerge. From an ecological-dynamics perspective, this variability may promote the attunement, adaptability, and perception–action regulation required to act under changing conditions (Chow et al., 2011; Renshaw et al., 2019; Pugliese et al., 2023). The findings therefore point to the importance of adaptive fidelity: maintaining coherent pedagogical principles while responding flexibly to learners rather than rigidly reproducing a fixed programme.

The adaptive stimulus-time threshold also contributes a temporal perspective on task performance. Accuracy indicates whether responses are correct, whereas this threshold indicates the exposure duration reached within the device's adaptive procedure; one outcome cannot be inferred from the other (Pugliese et al., 2025). At the same time, the present analysis was exploratory and retrospective, and the threshold remains an operational device measure rather than a fully reconstructed psychophysical threshold. Conclusions should therefore remain tied to the assessed tasks and should not be generalised to a single cognitive mechanism.

The results support further investigation of Nonlinear Pedagogy as an educational framework for integrating motor learning, cognitive engagement, autonomy, and participation through meaningful movement experiences. Future studies should combine rigorous measurement of adaptive temporal outcomes with detailed observation of teaching practice, including how teachers select, sequence, and modify constraints for learners with different needs. Such work would help determine not only whether nonlinear physical education interventions are effective, but how pedagogical decisions create the conditions under which children's motor and cognitive adaptability can develop over time.

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