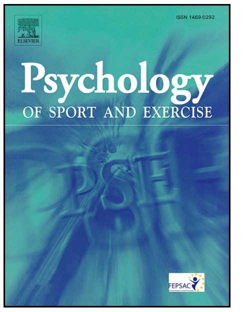

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Two years of physically active mathematics lessons enhance cognitive function and gross motor skills in primary school children.

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Abstract

Physically active lessons have been shown to enhance academic achievement. However, the effects on cognitive function and gross motor skill development remain unknown. The present study examined how the incorporation of physical activity bouts within Mathematics lessons affects cognitive function and gross motor skill development across 2 years in primary school children. Eighty-two children (6.6±0.3 y) were allocated to an intervention (n=36; completing 8 h/wk of physically active lessons) or control (n=46) group. A battery of cognitive function tests was completed, alongside the TGMD-3 to assess gross motor skills. Physically active Mathematics lessons led to greater improvements across all measures of cognition, when compared to the control group (digit span forwards, $p<0.001$, $d=1.5$; digit span backwards, $p=0.017$, $d=1.0$; free word recall: $p<0.001$, $d=1.3$; selective visual attention: $p<0.001$, $d=0.3$; verbal fluency: $p<0.001$, $d=0.9$; arithmetic: $p<0.001$, $d=1.8$). Furthermore, the intervention group demonstrated greater improvements in overall score on the TGMD-3 ($p<0.001$, $d=1.7$), as well as the locomotion ($p<0.001$, $d=1.1$) and object control ($p<0.001$, $d=1.5$) sub-scales. The physically active Mathematics lessons intervention appears to offer synergistic benefits in relation to cognitive and motor development, which are critical for optimal development in the early years.

Introduction

Through physical activity, cognitive and motor skills influence each other from childhood (Tomporowski & Pesce, 2019). Previous research has demonstrated that cognitive and motor development follow parallel timelines and, in particular, that it is possible for these key aspects of development to undergo an accelerated progression during developmental years (Ahnert et al., 2010). Furthermore, atypical or delayed cognitive development is linked with deficits in motor development, and vice versa (Piek et al., 2004). Therefore, the factors which influence the development of cognitive and motor skills during childhood are of great interest.

Given the multi-faceted benefits to physical, mental and social well-being associated with regular participation in physical activity (Biddle & Asare, 2011; Janssen & LeBlanc, 2010), it is concerning that globally more than 50% of children do not meet the recommended 60 min of moderate-vigorous intensity physical activity per day (Griffiths et al., 2013). Importantly, school provides an ideal setting for interventions aimed at increasing physical activity (Dobbins et al., 2013; Donnelly & Lambourne, 2011), not least due to the fact that there is a ‘captive audience’ and many opportunities for physical activity within the school day (e.g. Physical Education (PE) lessons, break time etc.). However, due to the great importance placed upon academic achievement in schools, opportunities for physical activity are often sacrificed to concentrate on more ‘academic’ subjects (Hardman et al., 2013; Harris, 2018; Howie & Pate, 2012).

The sacrifice of PE at the expense of academic pursuits is directly in opposition to the evidence suggesting that higher levels of physical activity (and subsequently enhanced physical fitness), as well as acute bouts of physical activity, have been shown to be beneficial for cognitive function (Donnelly et al., 2016; Li et al., 2017). Cognitive function is broadly defined as the mental processes involved in the acquisition of knowledge, manipulation of information, and reasoning (Kiely, 2014). Thus, it is unsurprising that higher levels of cognitive function have been associated with improved academic achievement (Best, Miller, & Naglieri 2011). One of the key domains of cognition is executive function; executive functions involve inhibition, working memory and cognitive flexibility (Diamond, 2013), and have been found to be associated with academic achievement in both reading and mathematics (Jacob & Parkinson, 2015). Subsequently, much interest has been placed on trying to optimise cognitive function in school-aged children, with one key intervention target being physical activity (Donnelly et al., 2016). Therefore, the incorporation of physical activity within the school day could be vital not only for physical health, but also cognitive function and academic performance.

Motor skills development in children and related cognitive development may be a mediating mechanism that can explain the positive effects of physical activity on academic performance. Indeed, previous studies have demonstrated that children's motor development and cognitive development are closely linked (Haapala et al., 2014; Jaakkola et al., 2015). Moreover, various cognitive skills, such as visuospatial skills and rapid automatized naming and memory skills, contribute to arithmetic learning (Lowrie et al., 2017; Zhang et al., 2017). In fact, during mathematical activities, children are focusing on, and shifting their attention between, dimensions of objects, (i.e., color and shape) or the precise characteristics of mathematical problems (Clements et al., 2016), requiring cognitive flexibility, a subset of executive function. Furthermore, visuomotor integration is strongly linked to concurrent and longitudinal mathematical achievement in children (Cameron et al., 2016; Carlson et al., 2015). Visuomotor integration can support mathematical skills because its concepts are also based on mental representations of objects and this is developed by interaction between children and physical objects in play (Hraste et al., 2018). Physical Education can support the development of speed of mental reactions and faster adaptation to new situations and improves orientation in combination with spatiotemporal relations. Indeed, previous research has reported the positive effect of implementing repetition and memorization strategies to promote numerical processing speed in physical activity interventions (Mullender-Wijnsma et al., 2015, 2016). Moreover, the review of Singh et al. (2019) found strong evidence for beneficial effects of physical activity on mathematics performance. Therefore, it could be assumed that key cognitive functions (i.e., executive function, memory and processing skills), could be positively influenced when physical activity and mathematics activities are combined.

One possible approach to incorporate physical activity in the curriculum, whilst also focusing on academic achievement, is the incorporation of physical activity bouts within the classroom (Bartholomew & Jowers, 2011). This approach is considered to be particularly effective when the new knowledge being taught is related to already well-known concepts (Dunlosky et al., 2013). Indeed, 'classroom-based physical activity', also referred to as 'physically active lessons', has been suggested as an effective intervention strategy to enhance both well-being and academic performance in young people (Martin & Murtagh, 2015; Routen et al., 2017). A number of meta-analytical and systematic reviews suggest that the incorporation of physical activity within the classroom enhances academic achievement/educational outcomes (Bedard et al., 2019; Norris et al., 2020; Singh et al., 2019; Watson et al., 2017), classroom behavior (Watson et al., 2017) and physical activity (Norris et al., 2020). However, there is great heterogeneity in the evidence base, possibly due to differences in intervention design and the outcome measures used. Whilst the beneficial effect on academic achievement is hypothesized to be due to enhanced cognitive function, the evidence base regarding the effect of physically active lessons on cognitive functioning is unclear. One possible reason for this is that fewer studies have measured cognitive outcomes compared to academic achievement (Daly-Smith et al., 2018; Norris et al., 2020; Singh et al., 2019). Furthermore, the interpretation of the studies conducted examining cognitive function can be difficult due to the multiple domains of cognitive performance measured and the variety in the measurement tools used (Daly-Smith et al., 2018; Norris et al., 2020; Singh et al., 2019).

A further possible benefit of the incorporation of physical activity within academic lessons is enhanced gross motor skill development. Gross motor skills are broadly defined as goal-directed movement patterns involving large whole-body movements, locomotion, and whole body stretches (Payne & Isaacs, 2017; Woodfield, 2004); and are thus viewed as important in the development of young people (Magistro et al., 2015; Stodden et al., 2008). Additionally, the development of gross motor skills is essential for health, psychosocial development, and well-being (Haga, 2008; Piek et al., 2006). Furthermore, it has been shown that increased opportunities to engage in physical activity enhances gross motor skill development in young people (Barnett et al., 2016). From a developmental point of view, childhood is a critical period for the development of gross motor skills, which are subsequently considered as essential building blocks of more complex movements (Clark & Metcalfe, 2002) and represent a key factor in the promotion of lifelong active lifestyles (Clark, 2005; Stodden et al., 2008). Moreover, motor skill development and acquisition provides the conditions necessary to produce long-term changes in the way individuals process information and make decisions (Tomporowski & Pesce, 2019), and is important for long-term adherence to physical activity (Clark, 2005; Stodden et al., 2008). However, the effect of the incorporation of physical activity within the classroom on gross motor skill development in young people has not been examined to date.

Furthermore, the potential synergistic benefits of cognitive and gross motor skill development are of great interest given that the allocation of cognitive resources required during motor skill acquisition is essential for enhancing the cognitive benefits obtained via motor skill-acquisition interventions are lasting (Tomporowski & Pesce, 2019). Therefore, the aim of the present study was to examine how the incorporation of physical activity bouts within the school curriculum (in Mathematics lessons) affects cognitive function and gross motor skill development across two-years in primary school children.

Design and Methods

A between subjects experimental research design was utilized in this study, in which two classes acted as the intervention group and two matched classes acted as the control group; to determine the effects of integrating physical activity bouts within Mathematics teaching on cognitive function and gross motor skill development in primary school children. The intervention consisted of integrating physical activity bouts in all Mathematics teaching hours (8 h per week), implemented for two school years (see Figure 1). The intervention was co-designed with the Mathematics and Physical Education teachers, and the school Headteacher; to enable every intervention lesson to be developed in accordance with the National Curriculum Guidelines for Primary School (DPCM n. 254, 2012). The activities were all administered by the teachers and were implemented in the classroom.

The control condition consisted of continuing the usual Mathematics teaching program, in line with the national curriculum. The two-year intervention protocol (full details available at DOI: 10.5281/zenodo.6811155) consisted of 75 different games, each with 4 possible variations. Each game was connected to a specific mathematical element. Each lesson consisted of a warm-up, an explanation, two main activities and a summative review at the end. At the beginning of each lesson, the warm-up was carried out by running, walking and/or performing other Physical Education/games-based activities (~ 10 minutes). In the explanatory part, the teacher explained a mathematics concept (~ 15 minutes). Subsequently, the teacher explained as well as clearly demonstrated the physically active learning task (~ 5 minutes). During first the main part of the lesson (lasting ~ 10 minutes), the children were applying the mathematical knowledge explained in the explanatory part through the physically active learning task. Subsequently, in the second main part of the lesson a variation of the physically active learning task activity was introduced (lasting ~ 10 minutes). In the summative part, the teacher summarised both the maths concept and the physically active learning task to the children (~ 5 minutes).

Across the two-year intervention, a number of key mathematical concepts were taught. For example, in the first six months (first year of elementary school) the lessons focused on: understanding, reading and writing natural numbers in decimal notation; and performing simple operations (e.g., addition and subtraction of numbers < 10), including the verbalization of simple calculation procedures. An example of a physically active lesson related to these topics was 'mathematical orienteering'. The goals of this physically active lesson were split in to physical, cognitive and mathematical goals. The physical goals were to focus on perceptual-motor control skills, oculo-motor skills, orientation and balance, and to consolidate basic motor patterns. The cognitive goals were to improve attention and memory, and to act promptly upon instructions from the teacher (executive function). Finally, the mathematical goals were to consolidate the concepts of units and tens, and addition and subtraction of numbers < 10. The physically active lesson consisted of children, in pairs, completing a mathematical-themed orienteering course. Each pair was provided with a map of two classrooms with the orienteering flags (control points). Each flag requires the children to solve math-related calculations or questions (using numbers < 10). The answers to each problem provide children with a route around 18 stations, using 18 maths questions. Children were required to write the answers to these questions in the table/map provided by the teacher.

[Insert Figure 1]

Participants

Power analysis using G-Power software showed that 36 participants for each group was sufficient to gather 80% power with a *p* value of 0.05 on our measures. Subsequently, four classes of the first grade of two Italian primary schools were involved in this study, resulting in a total of 82 children (age: 6.63 ± 0.28 y) participating in the study. The schools were both public schools in similar urban area with similar characteristic: two classes for each year and 20 (±3) children in each class. The four classes were randomly assigned, two to the intervention group (n = 36) and two to the control group (n = 46), with an intervention and a control group within each school. Table 1 provides the socio-demographic variables of participants. In both schools, the standard PE curriculum was 1 h per week and Mathematics curriculum was 8 h per week.

Informed consent was obtained from children's parents/guardians and assent was provided by the children themselves. The ethical committee of University of Torino approved the study (ID 100949).

Measurements

All measurements were made at four different time points: at the beginning (T1 – September 2017) and end (T2 – June 2018) of the first academic year; and at the beginning (T3 – September 2018) and end (T4 – June 2019) of the second academic year. At each testing point, all tests were performed on the same day, and measurements were performed at the same time of day for each participant.

Cognitive Function

The cognitive function tests were administered in the form of BVN 5-11 battery (Batteria di Valutazione Neuropsicologica per l'età evolutive; Bisiacchi et al. 2005). The BVN 5-11 is a test battery for the neuropsychological evaluation of the main cognitive functions (language, visual perception, memory, attention, higher executive functions, reading, writing and calculation) in children from 5 to 11 years old. It has previously been used successfully in a similar studies population (Arfé et al., 2019; Giordano et al., 2021; Russo et al., 2021) and shows acceptable agreement with the WISC-IV (Weschler Intelligence Scale for Children, version IV) (Bisiacchi et al. 2005). Participants completed the tests on a one-to-one basis with a trained experimenter. The testing battery took approximately 25 min to complete, and the tests were completed in the following order:

Digit Span: The Digit Span task (Bisiacchi et al., 2005) is divided into two tasks: forward digit span to measure attention and short-term memory; and backwards digit span to measure verbal working memory (Diamond, 2013; Samuel et al., 2017). A series of digits (e.g., 3,8,6) are verbally presented to the participant and then they attempt to recall and verbally repeat the correct sequence. In the forward digit span participants repeat the digit in the order presented whereas in the backward digit span participants are required to repeat the digits in the reverse order. Both the forward and backward digit span started with 3 digits in the target sequence. Participants were provided three opportunities at each sequence length. If the participant provides a correct answer for two sequences, they are provided a longer list. The test is completed when participants fail two of the three sequences presented. The participants received one point for every series of digits correctly recalled, resulting in a score from 0 to 7.

Free Word Recall: In the Free Recall Words test (Bisiacchi et al., 2005), participants were presented with a sheet containing 16 drawings. Participants were subsequently asked to name as many items as possible in 80 seconds. The participant received one point for every object recalled, resulting in a score from 0 to 16.

Selective Visual Attention: The Selective Visual Attention test (Bisiacchi et al., 2005) assesses this fundamental cognitive function that describes the tendency of visual processing to be confined largely to stimuli that are relevant to behavior (Moore & Zirnsak, 2017). In the test participants were asked to identify the 12 correct geometric symbols (which matched a target symbol) from a sheet with 80 symbols, in a maximum time of 60 seconds. The target (correct) symbol was a rhombus, showed at the top of the sheet. The participant received one point for every correct answer, resulting in a score from 0 to 12.

Categorical Verbal Fluency: The Categorical Verbal Fluency Test (Bisiacchi et al., 2005) assesses verbal fluency and semantic memory (Quaranta et al., 2019). In this test participants were asked to say, in 60 seconds, as many words as possible in a certain category. There were four categories used: colours, animals, fruits, and cities. The participant received one point for every correct answer and the total score was given by the sum all four trials.

Arithmetic Reasoning Ability: The Arithmetic test, taken from the WISC-IV (Wechsler, 2003), assesses the arithmetic reasoning ability of participants with a series of 34 problems that increase in difficulty. The participants had to solve mentally, without using pencil/paper/calculator, each problem in 30 seconds. The test ends when the participant provides four consecutive wrong answers. The participants received one point for every correct answer, resulting in a score from 0 to 34. This arithmetic test can be used to evaluate math development in children (Wechsler, 2003).

Gross Motor Skills

Gross motor skills were assessed with the Test of Gross Motor Development, third edition (TGMD-3) (Ulrich, 2017; Webster & Ulrich, 2017) in its Italian version (Magistro et al., 2018, 2020). In brief, the TGMD-3 is divided into two sub-scales (Magistro et al., 2020). The locomotor skill sub-scale composed of six skills: run, gallop, hop, horizontal jump, slide (judged on four performance criteria) and skip (judged on three criteria). The object control (ball skill) sub-scale was composed of seven skills: one hand forehand strike of self-bounced tennis ball, kick a stationary ball, overhand throw, underhand throw (judged on four criteria), two-hand strike of a stationary ball (judged on five criteria), one hand stationary dribble and two hand catch (judged on three criteria). At the beginning of each test section an accurate verbal description and demonstration of each skill was carried out by an examiner. Each child completed three trials, one for practice and then two formal trials. Only the scores of the two formal trials were recorded for the evaluation. Performances were observed and evaluated following the qualitative performance criteria for each TGMD-3 assessment skill: every criterion was scored based on whether it was fulfilled (score awarded = 1) or not (score awarded = 0). The total score for each item is given by the sum of both trials. Items' sums were used to calculate the score for the locomotor and ball control skills sub-scales as well as for the overall TGMD-3 scores. Confirmatory factor analysis confirmed the two-factor structure of TGMD-3 ($\chi2 = 916.284$, $df = 64$, $p < 0.001$, RMSEA = 0.050, 90% Confidence Intervals: 0.048, 0.053, CFI = 0.955; reliability for: locomotor sub-scale 0.996, ball sub-scale: 0.997, TGMD-3 total score 0.996).

Statistical Analyses

All data were analyzed using the SPSS computer package (SPSS v18.0; Chicago, IL). First, baseline differences between the intervention and control group were checked using an independent samples t-test, or chi-squared test, as appropriate. Subsequently, to test the effect of the intervention, a series of mixed method two-way (group [intervention vs. control] by time [time 1, 2, 3 and 4]) ANOVAs were performed for each outcome variable, with repeated measures for time. In addition, effect sizes were calculated (Cohen's d), as recommended to quantify the effectiveness of an intervention (Derzon et al., 2005). Cohen's d effect sizes were interpreted as per convention (negligible effect: ≥-0.15 to <0.15; small effect: ≥0.15 to <0.40; medium effect: ≥0.40 to <0.75; large effect: ≥0.75 to <1.10; very large effect: ≥1.10 to <1.45; and huge effect: >1.45). Independent samples T-test tests were also conducted as post-hoc testing to determine whether the difference between the intervention and control groups at each time point was significant. Further, two multivariate analysis of variance (MANOVA) analyses were conducted to examine the between group differences at time 4. All data are presented as mean ± standard deviation (unless otherwise stated) and statistical significance was accepted as $p < 0.05$, corrected for false discovery rate (FDR). Multiple comparison correction was performed using the FDR approach (Benjamini & Hochberg, 1995) given that FDR-based methods have been shown to be more powerful and sensitive than other available approaches to multiple statistical testing (Benjamini & Hochberg, 1995).

Results

The sociodemographic variables are presented in Table 1. All children, in both the intervention and control groups, attended at least 95% of the total lessons over the two years.

[Insert Table 1]

Cognitive Function

Data for each of the cognitive function tests, at each time point, in both the intervention and control groups, is shown in table 2. There were no significant differences between the intervention and control group at time point 1 (all $p > .05$). Table 2 presents mean scores (and standard error) of all the cognitive measurements for the intervention and control groups for the four measurement time points.

Digit Span Forward: Overall, participants in the intervention group scored higher on the digit span forward test compared to participants in the control group (main effect of group, $F(1, 80) = 8.46$, $p = 0.005$) and participants scores improved over time (main effect of time, $F(3, 240) = 81.28$, $p < 0.001$). Furthermore, the improvement in digit span forward score over time was greater in the intervention group compared to the control group (group * time interaction, $F(3, 240) = 16.99$, $p < 0.001$, $d = 1.5$ (huge); Figure 2a). MANOVA analyses indicated that digit span forward score was greater in the intervention group than the control group at time 4 (main effect of group, $F(1,80) = 37.07$, $p < 0.001$).

Digit Span Backward: Overall, participants in the intervention group scored higher on the digit span backward test compared to participants in the control group (main effect of group, $F(1, 80) = 22.70$, $p < 0.001$) and participants scores improved over time (main effect of time, $F(3, 240) = 69.35$, $p < 0.001$). Furthermore, the improvement in digit span backward score over time was greater in the intervention group compared to the control group (group * time interaction, $F(3, 240) = 13.93$, $p < 0.001$, $d = 1.0$ (large); Figure 2b). MANOVA analyses indicated that digit span backward score was greater in the intervention group than the control group at time 4 (main effect of group, $F(1,80) = 35.44$, $p < 0.001$).

Free Word Recall: Overall, participants in the intervention group scored higher on the free word recall test compared to participants in the control group (main effect of group, $F(1, 80) = 63.92$, $p < 0.001$) and participants scores improved over time (main effect of time, $F(3, 240) = 38.66$, $p < 0.001$). Furthermore, the improvement in free word recall test score over time was greater in the intervention group compared to the control group (group * time interaction, $F(3, 240) = 16.94$, $p < 0.001$, $d = 1.3$ (very large); Figure 2c). MANOVA analyses indicated that free word recall score was greater in the intervention group than the control group at time 4 (main effect of group, $F(1,80) = 72.41$, $p < 0.001$).

Selective Visual Attention: Overall, participants in the intervention group scored higher on the selective visual attention test compared to participants in the control group (main effect of group, $F(1, 80) = 21.23$, $p < 0.001$) and participants scores improved over time (main effect of time, $F(3, 240) = 48.65$, $p < 0.001$). Furthermore, the improvement in selective visual attention over time was greater in the intervention group compared to the control group (group * time interaction, $F(3, 240) = 7.71$, $p < 0.001$, $d = 0.3$ (small); Figure 2d). MANOVA analyses indicated that selective visual attention score was greater in the intervention group than the control group at time 4 (main effect of group, $F(1,80) = 4.20$, $p = 0.044$).

Categorical Verbal Fluency: Overall, participants in the intervention group scored higher on the categorical verbal fluency test compared to participants in the control group (main effect of group, $F(1, 80) = 76.35$, $p < 0.001$) and participants scores improved over time (main effect of time, $F(3, 240) = 97.28$, $p < 0.001$). Furthermore, the improvement in categorical verbal fluency over time was greater in the intervention group compared to the control group (group * time interaction, $F(3, 240) = 29.67$, $p < 0.001$, $d = 1.8$ (huge); Figure 2e). MANOVA analyses indicated that categorical verbal fluency score was greater in the intervention group than the control group at time 4 (main effect of group, $F(1,80) = 105.88$, $p < 0.001$).

Arithmetic Reasoning Ability: Overall, participants in the intervention group scored higher on the arithmetic reasoning ability test compared to participants in the control group (main effect of group, $F(1, 80) = 24.32$, $p < 0.001$) and participants scores improved over time (main effect of time, $F(3, 240) = 180.66$, $p < 0.001$). Furthermore, the improvement in arithmetic reasoning ability over time was greater in the intervention group compared to the control group (group * time interaction, $F(3, 240) = 14.43$, $p < 0.001$, $d = 0.9$ (large); Figure 2f). MANOVA analyses indicated that arithmetic reasoning ability score was greater in the intervention group than the control group at time 4 (main effect of group, $F(1,80) = 28.90$, $p < 0.001$).

[Insert Table 2 and Figure 2]

Gross motor skills

Data for the gross motor skill outcome measures from the TGMD-3 are displayed in Table 3. There was no difference in any of the gross motor skill outcome measures between the intervention and control groups at baseline (all $p > .05$).

Total Score: Overall, participants in the intervention group achieved a higher total score on the TGMD-3 compared to participants in the control group (main effect of group, $F(1, 80) = 25.99$, $p < 0.001$) and participants scores improved over time (main effect of time, $F(3, 240) = 83.25$, $p < 0.001$). Furthermore, the improvement in total score over time was greater in the intervention group compared to the control group (group * time interaction, $F(3, 240) = 35.75$, $p < 0.001$, $d = 1.7$ (huge); Figure 3a).

Locomotor Skill: Overall, participants in the intervention group achieved a higher locomotor skill sub-scale score on the TGMD-3 compared to participants in the control group (main effect of group, $F(1, 80) = 15.16$, $p < 0.001$) and participants scores improved over time (main effect of time, $F(3, 240) = 20.00$, $p < 0.001$). Furthermore, the improvement in locomotor skill sub-scale score over time was greater in the intervention group compared to the control group (group * time interaction, $F(3, 240) = 13.55$, $p < 0.001$, $d = 1.1$ (large); Figure 3b). MANOVA analyses indicated that locomotor skill sub-scale score was greater in the intervention group than the control group at time 4 (main effect of group, $F(1,80) = 16.79$, $p < 0.001$).

Object Control: Overall, participants in the intervention group achieved a higher object control sub-scale score on the TGMD-3 compared to participants in the control group (main effect of group, $F(1, 80) = 33.85$, $p < 0.001$) and participants scores improved over time (main effect of time, $F(3, 240) = 73.76$, $p < 0.001$). Furthermore, the improvement in object control sub-scale score over time was greater in the intervention group compared to the control group (group * time interaction, $F(3, 240) = 28.32$, $p < 0.001$, $d = 1.5$ (huge); Figure 3b). MANOVA analyses indicated that object control sub-scale score was greater in the intervention group than the control group at time 4 (main effect of group, $F(1,80) = 80.09$, $p < 0.001$).

[Insert Table 3 and Figure 3]

Discussion

The main finding of the present study was that physically active Mathematics lessons led to greater improvements in cognitive function and gross motor skill development over a 2-year period in the intervention group, when compared to a control group. The beneficial effects of physically active Mathematics lessons on cognitive function held true across a range of cognitive tests (assessing digit span, free word recall, selective visual attention, categorical verbal fluency and arithmetic reasoning ability); thus, suggesting that the beneficial effects exist across all cognitive domains (e.g. executive function, attention, perception and working memory). Furthermore, physically active Mathematics lessons led to greater improvements in overall gross motor skill development, as well as the locomotion and object control sub-elements. Moreover, considering the Arithmetic Reasoning Ability scores, as a secondary effect, the intervention led to stronger math development in the children. Therefore, the findings of the present study provide novel evidence that the inclusion of physical activity within the Mathematics curriculum is an effective strategy to enhance both cognition and gross motor skill development in elementary school children.

A key novel finding of the present study was that physically active Mathematics lessons enhanced a wide range of cognitive function measures over the 2-year follow-up period, when compared to the control group. Whilst previous research has demonstrated that physically active lessons lead to enhanced academic achievement/educational outcomes (Bedard et al., 2019; Norris et al., 2020; Singh et al., 2019; Watson et al., 2017) and classroom behavior (Watson et al., 2017), meta-analyses have concluded that the effect of physically active lessons on cognitive function remains unclear (Daly-Smith et al., 2018; Norris et al., 2020; Singh et al., 2019). However, the present study adds to the existing evidence base and provides important evidence that physically active lessons have beneficial effects across a range of domains of cognition (e.g. executive function, attention, perception, working memory), thus strengthening the argument that enhanced cognitive function may be the mechanism by which physically active lessons enhance academic achievement and educational outcomes. Previous studies suggested that after participation in PE interventions young people exhibit a more efficient use of neural resources underlying executive functions, reflected in enhanced neural activity in regions supporting attention and working memory functions (Hillman et al., 2014; Kamijo et al., 2011). PE activities combined with cognitive tasks would engage children’s executive functions, for example by activities within the physically active lessons that require information processing and working memory to perform successfully. These are believed to strengthen component processes of executive function and memory storage (Diamond & Lee, 2011). Indeed, sensorimotor experiences, regardless of their intensity, are linked to cognitive processes that underlie complex problem solving and strategy utilization and play a role in shaping knowledge (Gallese & Sinigaglia, 2011; Rosenbaum et al. 2012). This may explain the synergistic benefits in cognition, gross motor skills and mathematics ability (i.e. academic achievement) within the present study (Tomporowski & Pesce, 2019).

In addition, the present study is novel in that it documents the effects of an intervention over a 2-year follow-up period. Many previous studies have much shorter follow-up periods, with a median intervention length of 8 weeks in the meta-analysis of Norris et al (Norris et al., 2020). Indeed, the limited evidence base of longer-term interventions has no doubt contributed to the fact that longer interventions (> 8 weeks) demonstrated non-significant effects on educational outcomes, whilst shorter interventions (< 8 weeks) demonstrated significant benefits (Norris et al., 2020). This also suggests that the longer-term implementation of physical activity interventions in the school setting is challenging (Love et al., 2019). However, the present study provides evidence of a successfully implemented intervention that involved physically active Mathematics lessons over 2 academic years. Specifically, the findings of the present study demonstrate: that the beneficial effect of physical active lessons appear across a range of domains of cognition following a single school year (as evidenced by the differences between the intervention and control groups at time 2 in the present study); that the differences remain following the school holidays (time 3 in the present study); and that the differences continue to the end of the second school year (time 4 in the present study). This pattern was observed for all cognitive outcomes with the exception of digit span forwards, which was only enhanced at the 2-year follow-up point. It is hypothesized that this may be due to the different cognitive domains required for the digit span forward task (short-term auditory memory) compared to the other cognitive tasks (requiring various other cognitive domains). Furthermore, this could be because the digit span forward is a relatively simple cognitive task and it is thus only over two years of the intervention that the beneficial effects are seen, whereas for more complex cognitive tasks (e.g. digit span backwards and free word recall), the positive effects emerge earlier. This is in line with some previous work (Cooper et al., 2018) suggesting that more complex cognitive function are more likely to be positively influenced by physical activity. Therefore, the present study provides evidence that physically active lessons lead to enhanced cognition in young people, and that maintaining the physically active lessons over a 2-year time period leads to further benefits.

In addition to improved cognitive function, gross motor skills also improved. Recent research has shown that motor competence correlates with physical activity participation and health-related fitness in children (Robinson et al., 2015). While all children in this study improved their gross motor skills on average over the 2-year follow-up period, there were greater improvements seen in the children that participated in the physically active Mathematics lessons. The results presented in the current study suggest that participating in the physically active Mathematics lessons accelerates gross motor skills development. This is in accordance with previous work and meta-analyses (Chen et al., 2016; Dudley et al., 2011; Lopes et al., 2017) that showed the positive effect of combined physical activity and education on improving motor skill proficiency in primary school children. In line with the present results, previous studies on primary school children involved in extended and adapted physical activity lessons, found significant improvements in fundamental motor skills (Ericsson, 2008, 2011; van Beurden et al., 2003). More recently, the importance of physical activity and education in elementary school for learning life skills and developing positive behavioral patterns has been highlighted (UNESCO, 2017). The results of the present study suggest the potential impact that effective physically active lessons in primary school may have on the development of children gross motor skills, which is associated with greater general well-being, fitness, and physical activity levels (Barnett et al., 2016; Lopes et al., 2012, 2017; Robinson et al., 2015).

Considering the parallel development of cognitive ability and motor skills in this study, it is possible to hypothesise that gross motor skills are correlated with several aspects of cognitive function. Indeed, the development of motor skills is frequently considered separate from cognitive development. However, motor and cognitive development may be fundamentally inter-related because the cognitive processes that have functional implications must influence, and be influenced by, physical actions; and thus engage the motor system and perceptual functions (Geertsen et al., 2016). At the same time, motor control and motor skill learning processes might be influenced by different cognitive processes such as attention and decision making (Geertsen et al., 2016). Schmidt et al (2017) highlight how motor coordination was the best predictor for executive function ability in children, supporting the idea of shared information processes in both motor and cognitive control (Roebers & Kauer, 2009). Moreover, during development, cognitive and motor functions show similar improvement trajectories, and in situations when cognitive development is perturbed (e.g. by neurological disorders), motor development is usually negatively affected alongside this (Diamond, 2000). Indeed, it has been demonstrated that many tasks require parallel activation of cognitive-motor circuitries, and that the prefrontal cortex influences motor control and the cerebellum might have an important role for cognitive functions (Diamond, 2000). Considering both the results of the current study and the fact that cognitive ability is positively associated with motor skills, it is suggested that focusing on general motor skill development in children within the school curriculum should be a fundamental consideration.

As a secondary outcome, the present study also demonstrated an improvement in mathematical skills, as evidenced by improved Arithmetic Reasoning Ability scores. The importance of mathematical skills in modern societies is indisputable; indeed, mathematics is one of the core curricula subjects in any society (Beck et al., 2016). The results are in line with previous literature on the positive effects of integration of PE and maths (Sneck et al., 2019). Specifically, Beck and colleagues (Beck et al., 2016) reported positive effects of motor activities on academic performance and hypothesized that these may be connected to the effect of physical activity on visuospatial short-term memory and attention. Moreover, Da Cruz et al. (Da Cruz, 2017) demonstrated positive effects of a physical activity intervention on inhibition and mathematics fluency in children. Furthermore, in the study by Elofsson and colleagues (2018), it was reported that motor skills explained almost 16% of the variation in mathematical measures in children.

The results of the present study are in line with previous literature on the positive effect of integration of physically active lessons within the mathematics curriculum. Furthermore, the present study highlights that education should be integrated with physical activity. Failure to use integrated teaching could lead to insufficient realization of children's potential to improve their knowledge and skills. Schools have a critical role in introducing and integrating physical activity into children’s everyday lives. Therefore, to reduce the negative effects of a sedentary lifestyle, opportunities for the incorporation of physical activity into the school day, such as physically active lessons as examined here, should be examined and implemented in the regular school curriculum.

This is the first study to examine the effectiveness of physically active Mathematics lessons in children over two years. The strengths of this intervention study include both its length (2 years, longer than many previous studies), and the co-design approach to the development of the intervention that allowed the intervention to be economical and easily implemented by school staff. However, the present study also has limitations that need to be addressed. First, the children were not randomly assigned to the classes (rather the classes randomly assigned to the intervention or control group) and the sample may not be representative of a larger population (all classes were from the north of Italy). Another important constraint that may have influenced the results was the lack of control for habitual physical activity and diet over the two years of follow-up. Whilst this approach ensures ecological validity, future studies could address this by using measurements of habitual physical activity and diet during the follow-up. Furthermore, the effects on academic achievement (particularly in Mathematics) could be considered using standardized tests in future research. Lastly, fine motor skills were not measured in the present study. Fine motor skills are those which involve smaller muscle movements to hold and manipulate small objects with the use of hands and fingers (Strooband et al., 2020); and indeed previous work has demonstrated robust associations between fine motor skills and learning and developmental domains, such as gross motor skills (Wassenberg et al., 2005), school achievement (Barrocas et al., 2020; Luo et al., 2007) and executive functions (Cameron et al., 2012; Wassenberg et al., 2005). Therefore, future studies could include measurements of fine motor skills to understand the effectiveness of physically active (Mathematics) lessons to also impact fine motor skills, alongside the effects on gross motor skills demonstrated in the present study.

The results of this study suggest that two years of physically active Mathematics lessons enhances cognitive ability and gross motor skills in children to a greater extent than the usual school lessons and has provided insight on the potential positive impact of physically active lessons for children’s development. Schools should implement a curriculum that includes physically active lessons to have a positive impact on cognitive and motor development. Combining both movement and mathematics activities appears to offer synergistic benefits in relation to cognitive and motor communication development, which are critical for optimal development in the early years.

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Table 1: Sociodemographic variables of the intervention and control groups at baseline. Data are mean ± standard deviation.

	Control group (n = 46)	Intervention group (n = 36)	p value
Age (y)	6.64 ± 0.29	6.62 ± 0.26	0.913 [a]
Height (cm)	118.7 ± 4.8	116.6 ± 4.3	0.039 [a]
Body mass (kg)	23.4 ± 4.1	22.5 ± 4.3	0.383 [a]
BMI Classification			
Underweight	2 (4.3%)	3 (8.3%)	0.448 [b]
Normal weight	37 (80.4%)	29 (80.6%)	
Overweight/obese	7 (15.2%)	4 (11.1%)	
Sex			
Girls	21 (45.7%)	16 (44.4.%)	0.913 [b]
Boys	25 (54.3%)	20 (55.6%)	
Nationality			
Italian	41 (89.1%)	33 (91.7%)	0.701 [b]
Other	5 (10.9%)	3 (8.3%)	

[a] p value from independent samples t-test

[b] p value from chi-squared (χ^2) test

762 Table 2: Cognitive variables in the intervention and control groups across the two-year follow-up. Date are mean ± SEM.

Test	Group	T1		T2		T3		T4		Group * time interaction Corrected *p* value (FDR)	Effect size (Cohen's *d*) [a]	MANOVA Time 4 Mean Difference [95% CI] Corrected *p* value (FDR)
Digit span forwards	Control	4.0 ± 0.2	-	4.9 ± 0.1	-	4.9 ± 0.2	-	4.9 ± 0.2	*	< 0.001	1.5	1.43 [0.96, 1.88] $p < 0.001$
	Intervention	4.0 ± 0.2		5.2 ± 0.2		5.3 ± 0.2		6.4 ± 0.2				
Digit span backwards	Control	1.7 ± 0.1	-	2.1 ± 0.1	*	2.2 ± 0.1	*	2.8 ± 0.1	*	0.017	1.0	1.00 [0.66, 1.33] $p < 0.001$
	Intervention	2.1 ± 0.1		2.8 ± 0.1		2.8 ± 0.2		3.9 ± 0.1				
Free recall words	Control	5.7 ± 0.4	-	6.1 ± 0.3	*	6.1 ± 0.3	*	6.9 ± 0.3	*	< 0.001	1.3	4.46 [3.42, 5.51] $p < 0.001$
	Intervention	6.9 ± 0.4		9.6 ± 0.4		9.5 ± 0.4		11.4 ± 0.4				
Selective visual attention	Control	5.6 ± 0.4	-	5.9 ± 0.4	*	6.9 ± 0.4	*	9.1 ± 0.4	*	<0.001	0.3	1.34 [0.04, 2.64] $p = 0.044$
	Intervention	6.1 ± 0.4		9.0 ± 0.4		10.0 ± 0.4		10.5 ± 0.5				
Categorical verbal fluency	Control	26.7 ± 1.2	-	28.6 ± 1.1	*	29.6 ± 1.1	*	33.6 ± 1.2	*	< 0.001	0.9	17.94 [14.47, 21.41] $p < 0.001$
	Intervention	30.1 ± 1.3		42.3 ± 1.3		43.4 ± 1.3		51.6 ± 1.3				

Arithmetic test	Control	12.2 ± 0.5	-	13.9 ± 0.6	*	15.0 ± 0.6	*	17.7 ±0.6	*	< 0.001	1.8	5.12 [3.22, 7.01] *p* < 0.001
	Intervention	14.1 ± 0.6		18.2 ± 0.6		19.3 ± 0.6		22.8 ± 0.7				

All *p* values are reported as corrected for FDR (false Discovery Rate).

[a] Cohen's *d* effect size relates to the change between timepoint 1 and timepoint 4 between the control and intervention groups; * significant difference between intervention and control group (p < 0.05); T1: baseline (start of academic year 1); T2: end of academic year 1; T2: start of academic year 2; T4: end of academic year 2

Table 3: Gross motor skill variables in the intervention and control groups across the two-year follow-up. Data are mean ± SEM.

Test	Group	Timepoint T1		T2		T3		T4		Group * time interaction Corrected p value (FDR)	Effect size (Cohen's *d*) [a]	MANOVA Time 4 Mean Difference [95% CI] Corrected p value (FDR)
Total score	Control	70 ± 2	-	71 ± 2	*	72 ± 2	*	75 ± 1	*	< 0.001	1.7	
	Intervention	71 ± 2		85 ± 2		86 ± 2		94 ± 2				
Locomotion skills	Control	37 ± 1	-	37 ± 1	*	38 ± 1	*	39 ± 1	*	< 0.001	1.1	4.91 [2.53, 7.29] $p < 0.001$
	Intervention	37 ± 1		42 ± 1		43 ± 1		44 ± 1				
Object control - Ball skills	Control	33 ± 1	-	34 ± 1	*	34 ± 1	*	36 ± 1	*	< 0.001	1.5	13.95 [10.85, 17.02] $p < 0.001$
	Intervention	34 ± 1		43 ± 1		43 ± 1		50 ± 1				

[a] Cohen's *d* effect size relates to the change between timepoint 1 and timepoint 4 between the control and intervention groups; * significant difference between intervention and control group (p < 0.05); T1: baseline (start of academic year 1); T2: end of academic year 1; T2: start of academic year 2; T4: end of academic year 2

Figure 1: Flow Diagram of the study.

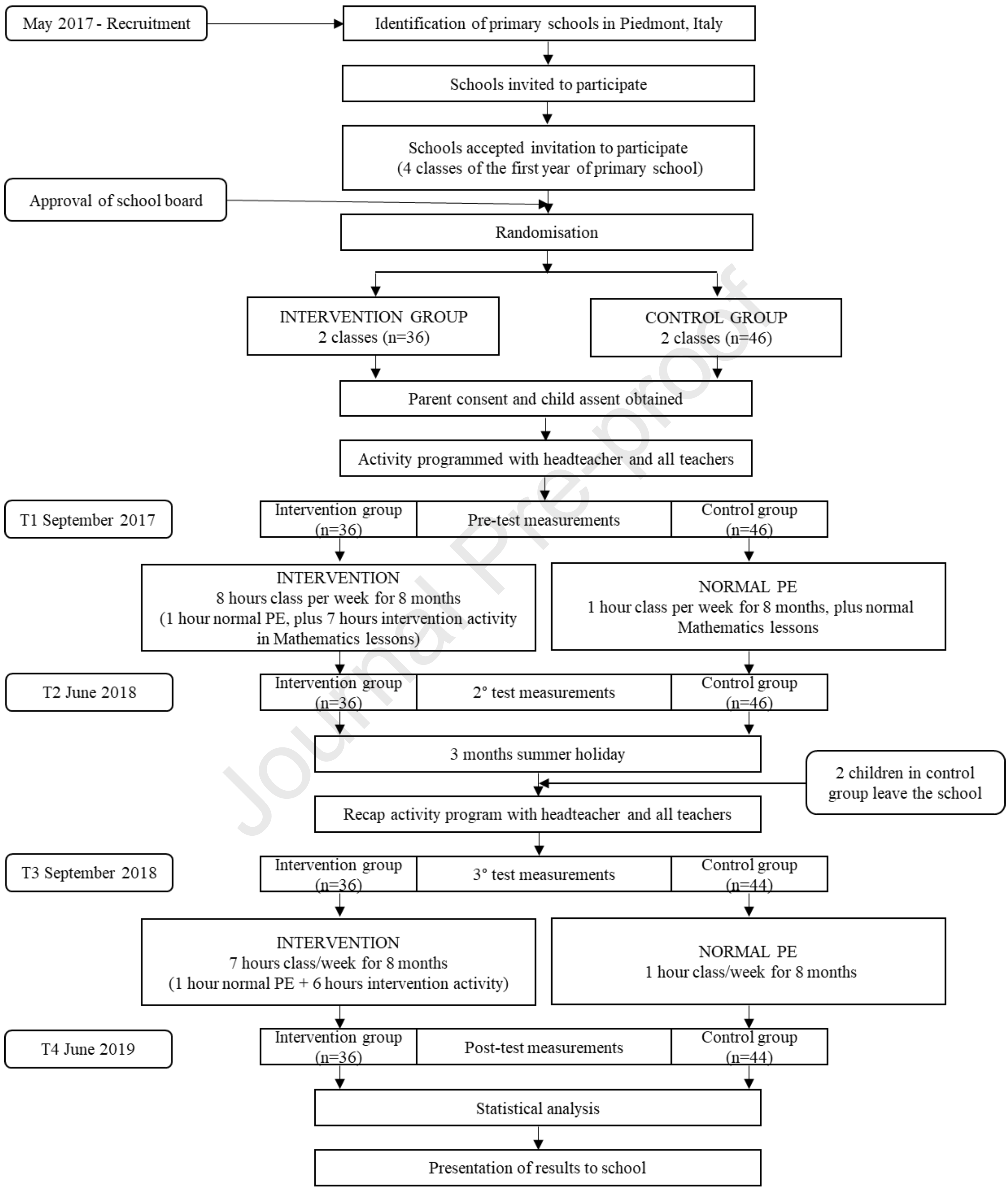


Figure 2: Cognitive measurements changes over time.

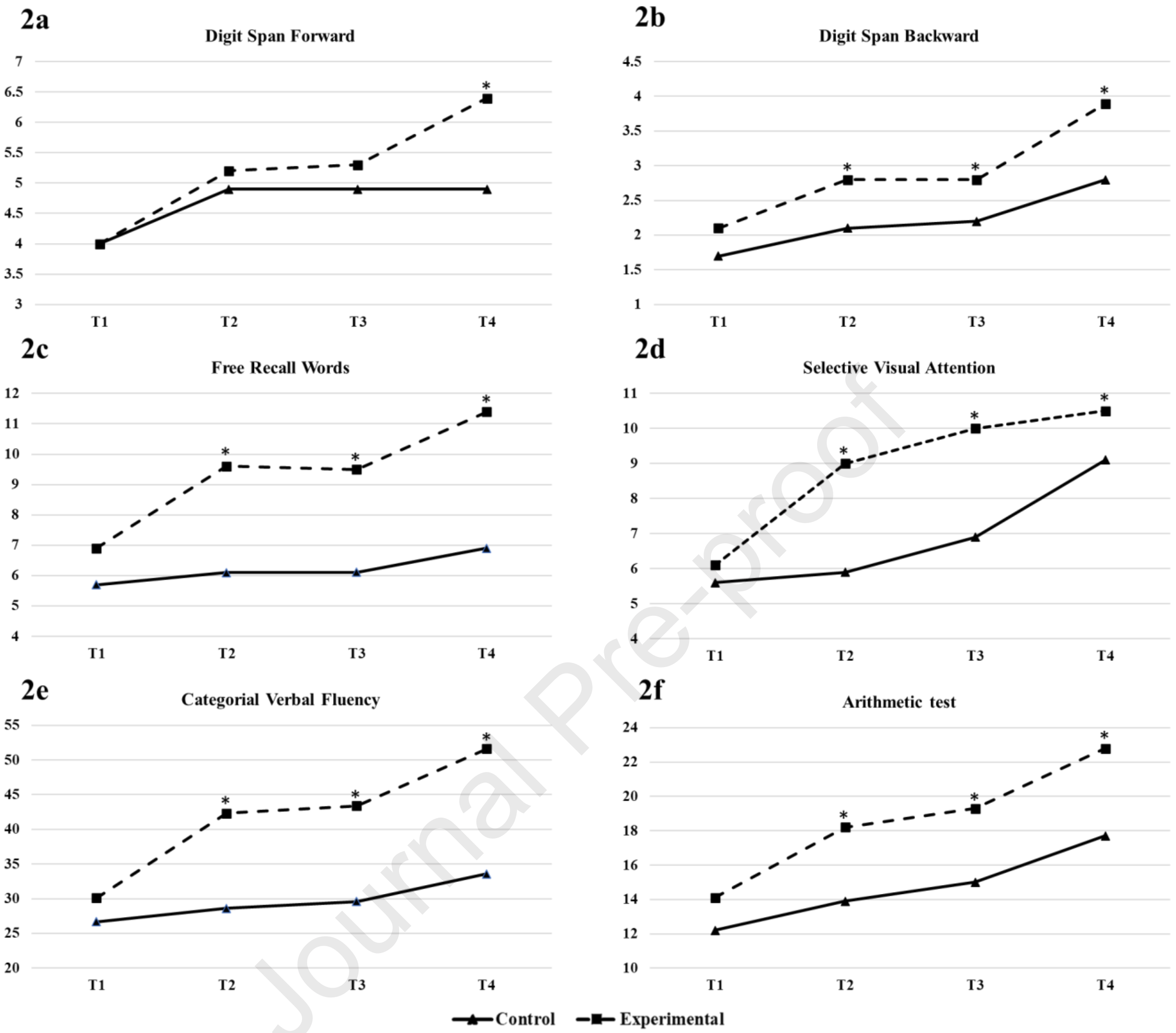
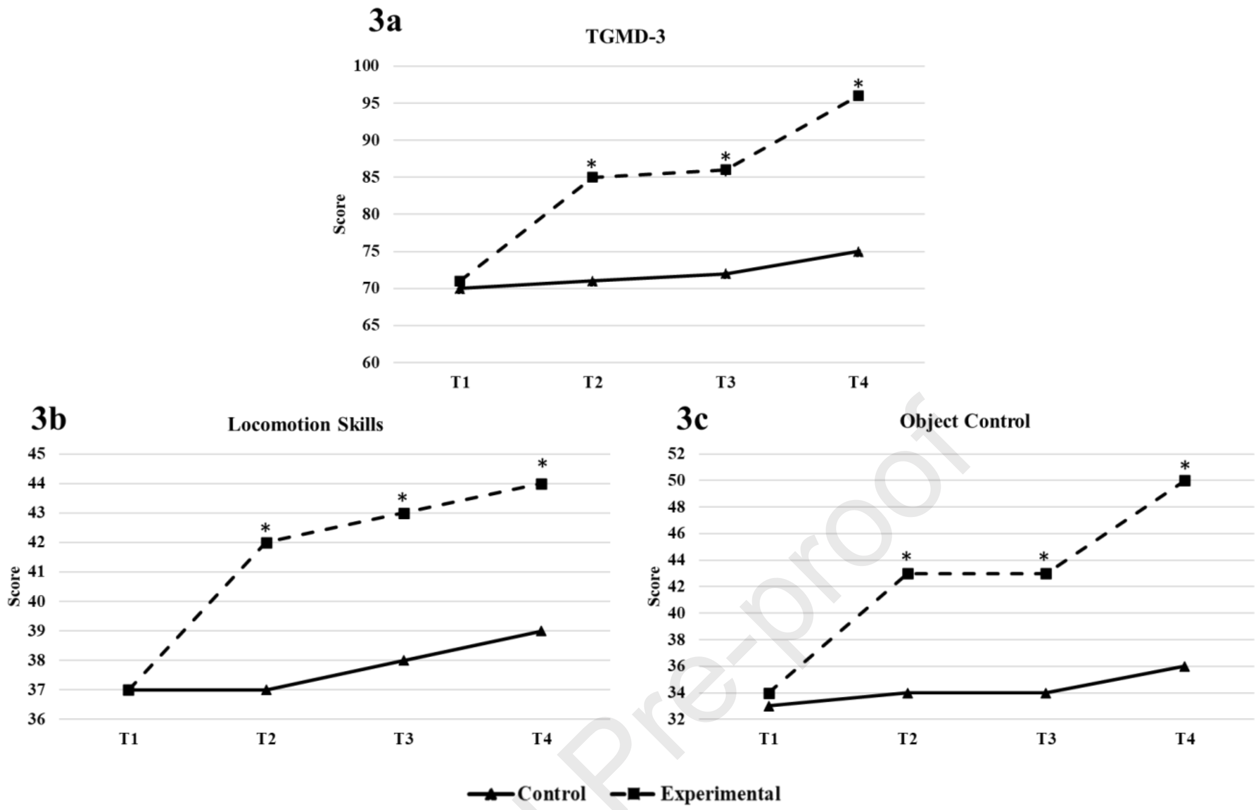


Figure 3: Gross motor skills change over time.



Highlights

- Physically active maths lessons synergistically improved cognition and motor skills
- Arithmetic ability was enhanced, the intervention may enhance academic achievement
- Implementation of physically active lessons in the curriculum is thus recommended

Conflict of interest

The authors declare that no potential conflicts of interest were disclosed.