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Fine motor skills and motor control networking in developmental age

Danilo Bondi[1] | **Claudio Robazza**[2] | **Christiane Lange-Küttner**[3,4] | **Tiziana Pietrangelo**[1]

[1]Department of Neuroscience, Imaging and Clinical Sciences, University "G. d'Annunzio" of Chieti-Pescara, Chieti, Italy

[2]Department of Medicine and Aging Sciences, University "G. d'Annunzio" of Chieti-Pescara, Chieti, Italy

[3]Department of Psychology, University of Greifswald, Germany

[4]Department of Psychology, University of Bremen, Bremen, Land Bremen, Germany

Correspondence
Danilo Bondi, Department of Neuroscience, Imaging and Clinical Sciences, University "G. d'Annunzio" of Chieti-Pescara, Via dei Vestini, 31, Chieti, 66100, Italy.
Email: danilo.bondi@unich.it

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Abstract

Objectives: We investigated the relationships between fine motor skills, fitness, anthropometrics, gender and perceived motor performance in school beginners. The aim of our study was to delineate whether and to what extent fine motor control would show meaningful synchrony with other motor variables in the age of onset of handwriting in school.

Methods: A sample of $N = 239$ of 6-to-8-year-old children were tested with an array of tasks measuring fine motor (i.e., dexterity and speed) and graphomotor performance (tracing on a tablet screen), anthropometric indexes, and fitness (shuttle run) measures. A subset of 95 children was also tested for perceived motor competence.

Results: In spite of an overall poor anthropometric condition, our participants were relatively fit. As expected, older children performed better in both, fine motor tasks and the shuttle test. The girls were better in fine motor skills, and an original speed-quality trade-off in the drawing was found. However, the magnitude of difference by grade was greater for boys' fine motor skills than those of girls'. A network analysis revealed three specific clusters, (1) perceived competencies, (2) fitness, and (3) fine motor skills.

Conclusions: Given the relative independence of these areas of physical performance, we suggest focusing on these three clusters as distinct areas of physical education. Fine motor skills deserve further consideration, especially at an early school age. We have demonstrated that network analysis and technology devices used to evaluate motor development are useful and meaningful tools.

1 | INTRODUCTION

We have considerable knowledge about how gross motor skills develop in children (Ghassabian et al., 2016; Smith & Thelen, 2003) and how to assess them (Griffiths et al., 2018). Thus, such results in gross motor skills become included in educational settings. In contrast, although some effort has been devoted to research on fine motor control development and interventions in babies and pre-school children (Strooband et al., 2020), less is known about fine motor skills in school age children. The aim of our study was to delineate whether and

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to what extent fine motor control would show meaningful synchrony with other motor variables because of the onset of handwriting in school.

The astonishing use of hands is a fundamental achievement of humankind: a wide-ranging sort of hand-based interaction with the environment led to a vital loop increasing our manual skills. In particular, the morphology and function of the thumb in manipulation and complex grasping is considered a cornerstone in functional evolutionary development (Marzke, 1992). Phenotypical features in postural and functional kinematics lead to the genesis of grapho-motor gestures, and the pattern of those gestures may reflect the developmental trajectories, allowing to assess grapho-motor levels (Vaivre-Douret et al., 2021). Increasing complexity and meaning in the use of tools was instrumental in the evolution of human intelligence (Lockman & Kahrs, 2017). Gender differences exist in performing grapho-motor tasks during developmental ages, with girls having an early advantage in performing fine motor tasks (Reikerås et al., 2017) and learning novel tasks (Flatters et al., 2014), while boys outperform girls in tasks requiring object control (such as throwing, Escolano-Pérez et al., 2021). The reasons lie both in biological factors—such as the differential involvement of visuo-motor integration (Giammarco et al., 2016)—and environmental factors, such as gender-differentiated expectations made by parents about suitable and proper motor tasks (Dinkel & Snyder, 2020).

Developing object manipulation skills in childhood promotes future physical activity (Barnett et al., 2009). Especially the advanced use of graphic tools has been playing a fundamental role in society: the complex use of such devices in drawing and handwriting was conducive to nearly every culture in this world (Milbrath & Council, 2003). This argument has been extended to digital technologies as they are integrated into school settings and online learning from home as innovative (and socially distanced) learning tools during the COVID pandemic (see also Scaradozzi et al., 2021).

The current study investigates how motor skills are related in children who have just begun school. This crucial transition point in child development when they are learning to write changes drawing from basic shapes and minimal detail to visually realistic drawing that captures modulated figure contours (Lange-Küttner et al., 2002; Toomela, 2002).

1.1 | Motor networks in development

From a kinesiological point of view, we can consider grapho-motor skills as special tool-related fine motor skills. Drawing, tracing, and writing result from an integrated input of visual and motor modalities (eye-hand coordination) during precise, small-scale movements. Defining fine motor skills, beyond grapho-motricity, other clusters involved are dexterity, manipulation of small objects, and speed-dominated skills in simple and very likely repetitive movements (Martzog et al., 2019).

Fine motor skills in school children consist of an interplay of spatio-temporal processing, visuo-motor integration, strength control, perceptual, and cognitive skills (Feder & Majnemer, 2007; Lange-Küttner, 1998; Tabatabaey-Mashadi et al., 2015). These related skills are a great example of networked neuromotor development. Different grapho-motor tasks such as writing and drawing lie on both common and distinct underlying neural circuits in the motor and posterior parietal. Drawing activates a ventral pathway responsible for overseeing and orienting in spatial fields, while writing activates a dorsal pathway that controls letter features (Raimo et al., 2021; Yuan & Brown, 2015). Moreover, delays and disturbances in the fine motor network are present in children with special needs such as ADHD and autism (Lange-Küttner & Kochhar, 2020) and are greatly correlated with low IQ, math and reading (Mayes et al., 2018; see also Suggate et al., 2018). Gaul and Issartel (2016) claimed that children's fine motor skill proficiency was not progressing at the expected rate given by normative data, over early school ages.

Thus, researchers have been using digital tablets and pen to acquire and evaluate the parameters pressure, velocity, and time in children's drawing and writing (Lange-Küttner, 1998; Tabatabaey-Mashadi et al., 2015). There is an emerging field of Artificial Intelligence in Education (AIED) for motor skills learning (Santos, 2016) that needs a clear characterization of the motor tasks in school children to set interactive technologies and foster advanced learning experiences. The multidisciplinary field of “graphonomics” needs to be linked within a broad spectrum of other motor skills and behavior (Van Gemmert & Contreras-Vidal, 2015). Recently, it has been suggested that grapho-motor performances can provide a paradigm to investigate motor skills that may deviate from the expected developmental trajectories (Bondi, Di Sano, Verratti, et al., 2020). While grapho-motor tasks, as other fine motor tasks, share common underlying pathways with gross-motor tasks rely on conscious and intentional motor strategy and control development, they develop differently in the way of how these shared roots emerge. Various factors such as the set of task constraints, goal-oriented decisions, motor synergies, optimal feedback, previous learning experience, and the adaptation processes influence general motor control (Todorov & Jordan, 2002), feeding into an aggregate performance in motor coordination tests. Scordella et al. (2015) showed a functional common basis of gross-motor and grapho-motor skills based on visual–spatial processes.

Such performances may be also differently influenced by the fitness and anthropometric status as relevance can be assumed in all coordinative motor skills (Augustijn et al., 2018). Overweight children perform poorly on motor tests and report greater body dissatisfaction and lower self-efficacy than their nonoverweight peers (Colella et al., 2009). Matarma et al. (2018) cogently demonstrated that, in young children, gross-motor coordination was related to anthropometric status, while fine motor coordination was not influenced by body weight. However, D'Hondt et al. (2008) reported childhood obesity to have a negative impact on fine motor performances, both with or without a simultaneous mechanical postural demand, suggesting a likely suffering from underlying perceptual-motor coordination difficulties in obese preschool children.

Among several determinant factors, Zaqout et al. (2016) highlighted BMI, age and sex as the strongest determinants of children's physical fitness, independent of physical activity. Boys often overestimate and girls underestimate their own competence regarding sports practice; this mismatch between objective competence and perceived competence may negatively influence health outcomes and motor skills in particular (Pesce et al., 2018). The perceptual judgment of sports rules is related to actual play experience, and gender difference influence the amount of sports experience (Lange-Küttner & Bosco, 2016).

1.2 | The current study

Because of the onset of handwriting, fine motor skills gained at preschool age are expected to change during the first scholastic years, ensuring a new proactive control of manual tasks (Meulenbroek & Van Galen, 1988). Thus, we explored the grapho-motor performance of early school-age children.

Given that the expression of fine motor skills and their development occur in different contexts and are thus task-dependent, our analysis included fine and gross motor tests as well as ancillary variables to assess the different underlying motor pathways. We analyzed the ability clusters of school children's graphonomics performance in relation to fitness and anthropometric status, as well as perceived competence. We also considered gender and age in early school-age children from 6 to 8 years of age. We hypothesized that the different domains of fine motor skills, including those related to graphonomics, were differently related to each other across age and gender, as the extent and time course of fine motor skills may have different development for boys and girls. We hypothesized a link between physical characteristics and performance with fine motor skills.

2 | METHODS

2.1 | Participants

The original sample consisted of 239 children of the first (all children of this grade were 6-to-7 years old) and second (all children of this grade were 7-to-8 years old) grade of First-Level School, living in the Abruzzo region, Italy. No child was years ahead or behind. All children had a similar preschool experience at local public schools. All schools were following similar curricula, that is, teaching of handwriting during the first and second grades. A total of 13 school classes were involved, according to school availability. All children were enrolled in the classrooms with their age peers chronologically matched. All children were invited to take part, with neither inclusion nor exclusion criteria. The number of boys and girls did not differ significantly, $\chi^2(1) = 0.235$, $p = .628$ (Table 1).

Participants' median weight and height were 25.9 kg and 123 cm, respectively (24.9 kg and 121 cm in first grade, 26.9 kg and 126 cm in second grade). Manual dominance was evaluated as a self-report by asking children to write their names. Splitting by manual dominance, 88.1% of children were right-handed (RH) and 11.9% left-handed (LH). In particular, the ratio of LH children was 14.4% in first grade and 8.9% in second grade, 10.6% in girls and 13.1% in boys. Because we focused on healthy motor behavior, the results of the six children with a certificate of disability were excluded from the data analysis. In this way, we were considering the setting of an inclusive experience as they were allowed to be part of the testing experience. In the remaining sample there were no children with graphic or writing problems.

We randomly selected a subgroup of seven school classes to administer the Pictorial Scale of Perceived

TABLE 1 Boys and girls distribution across school grades

	Grade		
Gender	**First**	**Second**	**Total**
Girls	60	52	112
Boys	72	55	127
Total	132	107	239

Movement Skill Competence-2 (PMSC-2; Barnett, Robinson, et al., 2015). This was due to time and logistic constraints, Thus, only a subsample of $n = 95$ children (42% of the first grade and 58% of the second grade, 49% boys and 51% girls, 88% RH and 12% LH) completed this test.

2.2 | Materials and apparatus

The grapho-motor test was performed on a tablet PC, carried out following an established procedure (Giammarco et al., 2016) which involved a blank page with a square and a diamond represented in four gray segments shown on a tablet screen (Samsung Galaxy note, 10.1 in., 1280 × 800). The software was developed by the authors of the cited study (Giammarco et al., 2016) and got by them, who also positively tested the retest reliability with Primary school children. The size of the square and diamond were large enough to cover the entire screen of the tablet (see the original article for a deeper description and images). Children were supposed to redraw the shapes with a digital pen.

The Pictorial Scale of Perceived Movement Skill Competence-2 (PMSC-2; Barnett, Robinson, et al., 2015) was administered on printed A4 sheets. It is a widely used pictorial scale used to assess perceived competence on *object control*—hand competence skills (C), *locomotor*—dynamic leg competence skills (*L*), and other skills involved in free time, *active play* activities (A). Anthropometric testing required a measuring tape and a portable scale. Reliability of this scale was demonstrated for the age group of the present study (internal consistency of 0.73 and test–retest reliability of 0.83 for children aged 5–7 years; Barnett, Ridgers, et al., 2015; internal consistency of 0.72 and test–retest reliability of 0.73 for children aged 5–8 years: Barnett, Robinson, et al., 2015).

Fine motor coordination was assessed with two tests: a transitive (tool-related) action test (*Floppy*) and an intransitive (non-tool related) action test (*Thumb*). These tests required a box of floppy disks and a stopwatch; they have been already used for testing children of similar ages (Bondi, Robazza, & Pietrangelo, 2020; Bondi, Robazza, Russo, et al., 2020). For procedural details, see the following sections.

2.3 | Procedure

The cross-sectional design encompassed physiological, anthropometric, and motor measurements. The time frame of our study consisted of 4–6 months after the onset of the scholastic season. The study ethics was approved by the Italian Olympic Committee (CONI) and by the regional Board of Education of the Italian Ministry of Education, University and Research (MIUR), Abruzzo region, Italy. Permission was obtained by the school administration and informed consent was signed by the parents of the children. The study conformed to the Declaration of Helsinki.

Children's motor skills were tested individually. Children were assessed at their school in the presence of the teachers, during regular physical education time. The assessment of the subsample of $N = 95$ children who completed the PMSC-2 assessment procedure took around 10–15 min per child.

In the first data collection session, after the PMSC-2 was administered, we collected anthropometric measures and conducted the fitness test (*Shuttle* test, see below). In the following data collection session, the grapho-motor tablet task and the fine motor tasks were given in random order. The test–retest reliability of *Floppy* and *Thumb* tests was assessed by the same observer in three consecutive trials during this data collection session: the Intraclass Correlation Coefficients (ICCs) were good-to-excellent (Koo & Li, 2016), see Table 2. Therefore, the data of first repetition were used for further analyses. The total testing time of the second data collection session was about 15 min per child, plus 5 min for retest.

Of the entire sample, we collected height, weight, and waist circumference as anthropometric data, then we calculated body mass index (*BMI*) and waist-to-height ratio (*WtHR*; Mamen & Fredriksen, 2018). We assessed speed and agility through the 4 × 10 m shuttle run test (*Shuttle*; Ruiz et al., 2011), that is a running and turning test at greatest speed: briefly, two parallel lines are drawn on the floor 10 m apart; the child runs from the starting to the other line and returns with a sponge; the sponge is changed by another sponge, then the child goes back running to the opposite line and changes the sponge by another one and finally runs back to the start. The time to complete the task was the outcome variable.

The grapho-motor test started with a familiarization phase and thereafter consisted of two trials: the first trial

TABLE 2 Reliability coefficients of *floppy* and *thumb* tests ($N = 233$)

Test	Grade		
	First	Second	Overall
Floppy	0.95	0.76	0.88
Thumb	0.96	0.90	0.93

TABLE 3 Exploratory factor analysis for four tablet test parameters ($N = 233$)

	Factor
	1
Strokes	−0.749
Pressure	/
Speed	0.997
Quality	0.572

Note: Root mean square error of approximation (RMSEA) = .102; Tucker-Lewis index (TLI) = .947; χ^2 (2, 239) = 5.97, $p = .050$.

required to trace as accurate as possible (*Best*); the second trial required to trace as accurate as possible with a higher velocity (*Fast*). All lines drawn with the pen on the tablet screen were stored as strokes. The pressure and the speed exerted on the pen were calculated as scores of the average over the length of lines. For both trials, we acquired the measures of the number of *Strokes*, the *Pressure*, the *Speed* as well as the mean oscillation (quadratic deviation of the points) from the graphic line (*Quality*). Recording data were processed whenever the digital pen exerted a pressure on the screen. Using this tool permitted us to simulate the effective functional parameters of drawing and to measure the required objective parameters.

The *Floppy* test was used to assess manual dexterity (Martzog et al., 2019). It required participants to insert 12 floppy disks one at a time in the floppy box, as fast as possible, holding the box while inserting the disks (to provide a different role for each hand). The rationale for using this test was based on manual dexterity assessment and, with respect to similar tests—like the coins task of M-ABC 2 battery—the present test was not affected by motor experience of common tasks (Zoia et al., 2018). This test required a strategy to better carry out the task, with increased difficulty during execution (as the disks are placed into the box, the empty space is reduced).

The *Thumb* test was used to assess upper limb coordination, as well as speed-dominated skills (Martzog et al., 2019). Participants were required to touch each finger of one hand with the thumb of the same hand in an alternating pattern (5th, 4th, 3rd, and then 2nd finger, and reverse), as fast as possible. The rationale for using this test was based on the visual-motor control assessment of the BOT-2 battery (Bruininks & Bruininks, 2005) which is a common task in clinical assessment (finger–thumb test) and motor rehabilitation. As for the *Floppy* test, the outcome variable was time of completing as measured with a stopwatch.

2.4 | Data generation

We conducted an Exploratory Factor Analysis (EFA) on four tablet test parameters, see Table 3, with a Maximum Likelihood rotation. We obtained only one fine motor skills factor, based on an eigenvalue >1 and on the scree plot.

We then conducted a Confirmatory Structural Equation Modeling (SEM), considering the expected correlations, and putting into the model the factor from the EFA in *Best* condition, the same factor in *Fast* condition, the hypothesized relationships between *Best* and *Fast* conditions. We tested age and gender in the model, evaluating fit measures to choose the best model. Such measures suggested including gender and the correlation between Speed and Quality in Best condition. With more than two predictors, it is possible to obtain values larger than +1, as the value of the path between TPB and Speed-B. Error calculation method: Robust; estimator: Diagonally Weighted Least Squares (DWLS). Fit measures: RMSEA = .042, SRMR = .050, TLI = .987, CFI = .995, GFI = .989; χ^2 (9, 239) = 11.56, $p = .239$. *TPB*: Tablet Performance Best; *TPF*: Tablet Performance Fast; B: Best; F: Fast. Four equations were produced:

- Girls *TPB*: *Quality* + (38.28 × *Speed*) − (11.62 × *Strokes*)
- Girls *TPF*: *Quality* + (65.10 × *Speed*) − (2.76 × *Strokes*)
- Boys *TPB*: *Quality* + (55.66 × *Speed*) − (22.78 × *Strokes*)
- Boys *TPF*: *Quality* + (70.04 × *Speed*) − (2.22 × *Strokes*)

We evaluated the fit measures for different models, concluding that the best model was the one shown in Figure 1.

We applied the assumption of normality and multivariate normality, and subsequently a nonparanormal transformation (Liu et al., 2009) before conducting correlations. The coefficients in Figure 1 were used to build unweighted undirected graphs. The analysis revealed that gender had to be taken into account when defining the structural model of tracing performance. Finally, the four equations were used to calculate *TPB* and *TPF*, separately for both boys and girls.

2.5 | Data analysis

Statistical analyses were carried out using GraphPad Prism Software, version 9 (GraphPad Software, La Jolla, USA), R-based open-source software Jamovi (https://www.jamovi.org) and Jasp (https://jasp-stats.org). Data

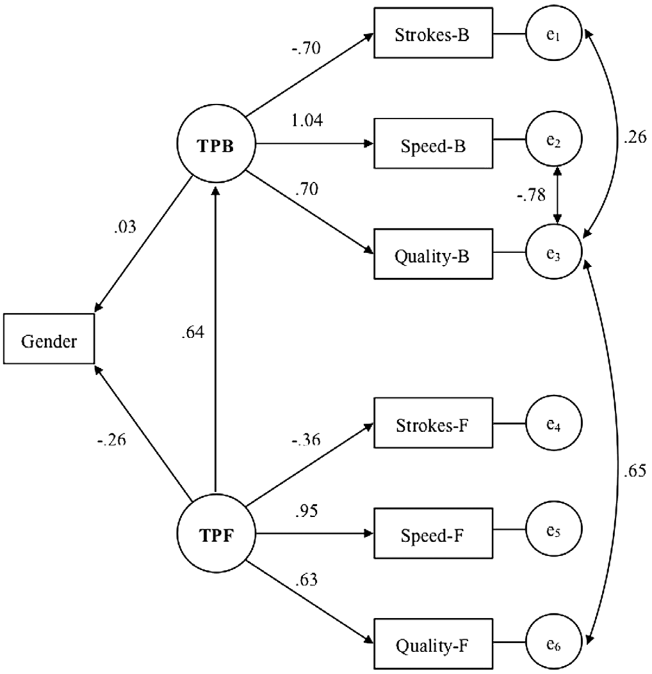

FIGURE 1 Confirmatory structural equation modeling (SEM) of tablet test parameters. P: Percentile; *TPB*: Tablet Performance Best; *TPF*: Tablet Performance Fast; BMI: Body mass index; the showed numbers are the standardized coefficient (standardizing both label and observed variables)

distributions were analyzed using Shapiro–Wilk and D'Agostino-Pearson methods. Analysis of outliers was conducted with the ROUT method, implemented in Prism (Motulsky & Brown, 2006). An alpha value of .05 was considered as statistically significant.

Considering the assumption check, robust ANOVA and robust *t*-test were chosen to run the comparison tests. In particular, a series of robust ANOVAs (median method) were carried out to test the gender × age effect on *TPB*, *TPF*, *Shuttle*, *Floppy*, *Thumb*, *BMI*, *WtHR*, *Control*, *Locomotor*, *Active play*. In case of a significant interaction effect, post-hoc analyses with Tukey correction for multiple comparisons were conducted. Robust *t*-tests (Yuen's test with 0.1 trimmed proportion and median method), in addition to the nonparametric Mann–Whitney *U* test, were carried out for the left versus right-side manual dominance effect on *TPB*, *TPF*, *Shuttle*, *Floppy*, *Thumb*, *BMI*, and *WtHR*.

The links between graphonomic outcomes, other fine motor skills, fitness, and anthropometric status, as well as perceived competence, were addressed with network models, using correlations as estimators. Further network analyses were conducted with *TPB*, *TPF*, *Shuttle*, *Floppy*, *Thumb*, *BMI* and *WtHR*, splitting by age and gender. PMSC-2 parameters were excluded from the split networks because of the smaller sample sizes of the subgroups. For the details of network analysis, refer to the figure legends.

3 | RESULTS

The BMI values of participants were compared to the normative values of provided by the World Health Organization (WHO, 2007). Our P50 values ranged between normative P50 and P75 matching for the same gender and age: BMI of our participants was therefore higher than this reference. We further classified the children according to the obesity cut-off norms of P97 from the WHO reference (Valerio et al., 2018). As a result, 24.76% of children in our sample had obesity.

The WtHR values of our participants were compared to the recent values reported by Santomauro et al. (2017) on Italian children from Tuscany, a region in central Italy, north of Abruzzo region. Our P50 values ranged between their P50 and P75 matching for the same gender and age. Therefore, WtHR values of our participants were higher than this reference. We further characterized the participants according to the health hazard cut-off of 0.50 (Maffeis et al., 2008). We found 14.35% of children to be at metabolic risk.

Shuttle performances of participants were compared to international norms for this task (Kolimechkov et al., 2019). Median of boys in first grade were between P30 and P40 of that reference, girls in first grade were between P50 and P60; boys in second grade were between P50 and P60, girls in second grade were between P60 and P70. Shuttle performance was therefore overall higher than this reference, except for boys in the school entrance class.

PMSC-2 values of participants were compared to two different samples of school children data reported by Barnett, Robinson, et al. (2015). Australian children rated on average 19.9 in object control subscale (*C*) and 20.7 in locomotor subscale (*L*); American children rated 20.5 in *C* and 20.7 in *L*; present study, children rated 20.4 in *C* and 22.2 in *L*. Participants of our study therefore rated higher on locomotor subscale of PMSC-2 than these reference values.

3.1 | Comparison by gender and grade

Group means are shown in Tables 4 and 5. Results were analyzed through a series of robust ANOVAs with the median method. All the *p* values of statistical comparisons are shown in Tables S1 and S2, Supporting

TABLE 4 Results of the comparisons by grade and gender, $N = 239$

			Graphonomics		Fine motor skills		Anthropometrics		Fitness
		Grade	**TPB**	**TPF**	**Floppy *time* (s)**	**Thumb *time* (s)**	**BMI (kg/m^2)**	**WtHR**	**Shuttle *time* (s)**
*Q*1	Girls	First	979	1794	19.9	8.62	15.7	0.443	15.2
		Second	832	1638	19.2	7.53	15.5	0.429	13.6
	Boys	First	413	906	21.1	8.58	15.9	0.447	14.5
		Second	348	978	19.6	7.89	16.2	0.465	13.1
Median	Girls	First	1292	2424	22.8	10.00	17.2	0.468	15.8
		Second	1291	2080	20.0	8.29	16.5	0.448	14.4
	Boys	First	649	1191	24.2	10.6	16.7	0.464	15.6
		Second	848	1115	21.5	9.29	18.0	0.478	13.9
*Q*3	Girls	First	1740	2908	25.4	11.6	19.4	0.492	16.6
		Second	1643	2590	22.7	9.81	18.9	0.468	15.8
	Boys	First	1011	1711	27.5	12.4	17.9	0.486	16.9
		Second	1066	1489	24.3	10.8	20.4	0.499	15.2
Median (whole sample)			983	1643	22.4	9.4	16.9	0.466	15.1

Abbreviations: BMI, body mass index; *Q*, quartile; *TPB*, Tablet Performance Best; *TPF*, Tablet Performance Fast; WtHR, waist-to-height ratio.

TABLE 5 Results of the comparisons in PMSC questionnaire by grade and gender, $N = 95$

		Grade	***C***	***L***	***A***
*Q*1	Girls	First	16.0	20.5	17.0
		Second	19.0	21.0	17.0
	Boys	First	20.0	20.0	15.0
		Second	20.5	22.5	16.0
Mdn	Girls	First	19.0	23.0	19.0
		Second	20.5	23.0	20.0
	Boys	First	21.0	23.0	18.5
		Second	22.0	23.0	19.0
*Q*3	Girls	First	21.5	24.0	22.0
		Second	21.0	24.0	23.0
	Boys	First	23.0	24.0	22.8
		Second	23.0	24.0	21.5
Mdn (whole sample)			21.0	23.0	19.0

Abbreviations: *A*, active play; *C*, object control; *L*, locomotor; Mdn, median; *Q*, quartile.

Information. Box and whiskers plots of the results split by gender and grade are shown in Figure 2

Overall, the higher the speed of the pen on the screen, the lower the quality of drawing. Regarding the tablet test, we found strong differences by gender in both the *TPB* and *TPF* ($Q_{1,188} = 23.50$, $p < .001$, partial $\eta^2 = .239$; $Q_{1,165} = 59.52$, $p < .001$, partial $\eta^2 = .376$). The gender × age interaction was not significant ($p = .127$ and $p = .323$, respectively).

Task-specific analyses showed that older children (*Mdn* = 14.31 s) performed better than younger ones (*Mdn* = 15.78 s) in the *Shuttle* test which measures the fitness domains of speed and agility ($Q_{1,204} = 27.17$, $p < .001$, partial $\eta^2 = .139$). Older children ($Q_{1,178} = 15.33$, $p = .040$, partial $\eta^2 = .042$) and girls ($Q_{1,178} = 4.22$, $p < .001$, partial $\eta^2 = .042$) performed better in the *Floppy* test which measures fine coordination on a tool-related (namely transitive) action. Both boys and girls performed better with age in the *Thumb* test ($Q_{1,191} = \text{df1} = 1$, $\text{df2} = 191$, $p < .001$, partial $\eta^2 = .053$) which measures fine coordination of fingers on one hand without holding a tool (namely intransitive action).

There was a main effect of gender on the WtHR (girls showed a higher WtHR than boys, $Q_{1,200} = 4.74$, $p = .029$, partial $\eta^2 = .024$), and a significant two-way interaction ($Q_{1,198} = 8.17$, $p = .004$, partial $\eta^2 = .037$); post-hoc analysis revealed no significant difference between boys and girls in the first grade, whereas boys showed higher WtHR values (*Mdn* = 0.48) than girls (*Mdn* = 0.45) in the second grade ($p_{\text{Tukey}} = .005$, Cohen's $d = 0.699$).

There was a difference between boys and girls by sex in the BMI (gender × age comparison: $Q_{1,199} = 6.49$, $p = .011$, partial $\eta^2 = .035$); post-hoc analysis revealed no significant difference in the first grade, but a tendency for girls to show lower BMI values (*Mdn* = 16.5 kg/m^2) than boys (*Mdn* = 18.0 kg/m^2) in the second grade ($p_{\text{Tukey}} = .082$, Cohen's $d = 0.496$).

For what concerns the PMSC-2 test, boys perceived their object control skills to be higher than girls

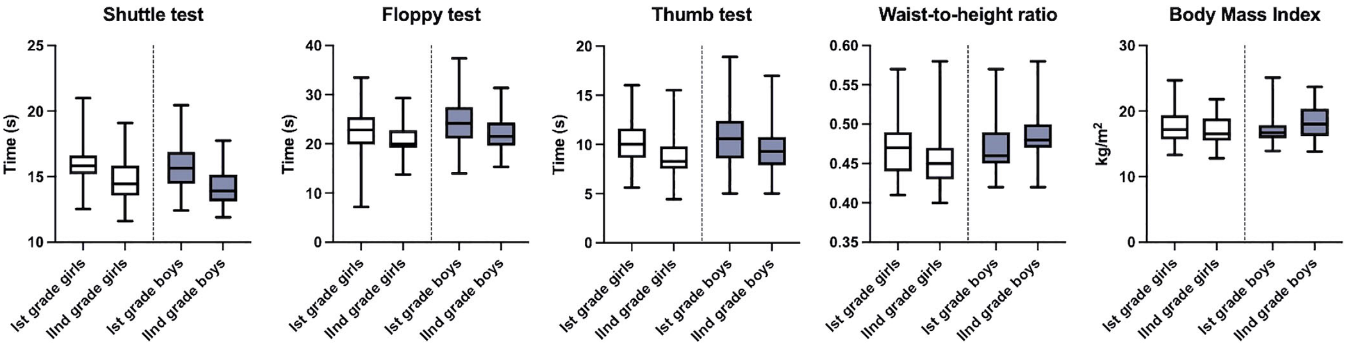

FIGURE 2 Box and whiskers plots of anthropometric and motor skills results. Each of the three panels represent min-to-max lines and median with IQR boxes. For each dataset, girls (white boxes) and boys (gray boxes) results are shown split by school grade

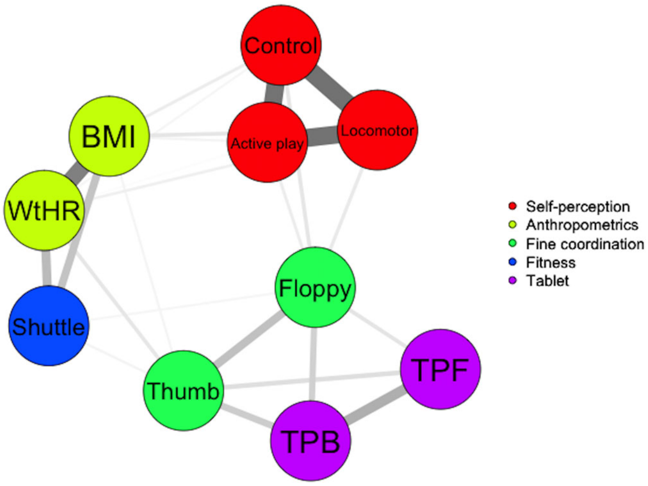

FIGURE 3 Network plot of the 10 parameters. The bolder the line, the higher the weight of the correlation between nodes. Nodes of the same colors belong to the same group, according to clustering measures of the analysis. Nodes are positioned using the Fruchterman-Reingold algorithm, based on the strength of connections. *TPB*: Tablet Performance Best; *TPF*: Tablet Performance Fast; BMI: Body mass index; WtHR: Waist-to-height ratio

($Mdn = 22$ vs. 20; $Q_{1,93} = 4.45$, $p = .035$, partial $\eta^2 = .093$), see Table 5, while no significant differences were found in Locomotor or Active play subscales.

TABLE 6 Centrality measures per variable in overall network analysis

	Closeness	Strength
Active play	−0.091	0.907
BMI	0.859	0.410
Control	−0.180	1.031
Floppy	1.407	0.019
Locomotor	0.788	1.414
Shuttle	−0.604	0.997
TPB	−0.729	0.831
TPF	−2.121	1.736
Thumb	0.365	0.428
WtHR	0.305	0.250

Note: "Closeness" refers to the inverse of the "peripherality" (the sum of the shortest paths starting from the node of interest), "strength" refers to the centrality "degree" (sum of absolute weights) of the node of interest. Abbreviations: BMI, body mass index; *TPB*, Tablet Performance Best; *TPF*, Tablet Performance Fast; *WtHR*, waist-to-height ratio.

3.2 | Network analysis

To analyze the synchronous relationships between variables, we conducted a network analysis. In Figures 2 and 3, the task components that refer to one test are depicted in the same color. Network clusters are marked by the connections between these components, with thicker lines showing stronger connections. The analysis of the sample of $N = 95$ revealed three fundamental clusters. One is the *PMSC-2 cluster*, with the three subscales strongly linked to each other with the following weights: Locomotor and Control = .851, Locomotor and Active play = .894, Control and Active play = .879. The second is the *Fitness cluster*, with the anthropometric measures and the Shuttle test showing moderate links of the Shuttle test with both BMI (weight = .396) and WtHR (weight = .399), and a strong link between WtHR and BMI (weight = .902). Finally, the third fundamental cluster is the *Fine Motor Control cluster*, with moderate links between the different tablet and floppy parameters.

In particular, the following weights were observed: Floppy and Thumb = .589, Floppy and TPB = .547, Floppy and TPF = .368, Thumb and TPB = .522, Thumb and TPF = .510, TPB and TPF = .433. The centrality measures revealed Floppy to be the most central, although weakly, node of the network (see Table 6).

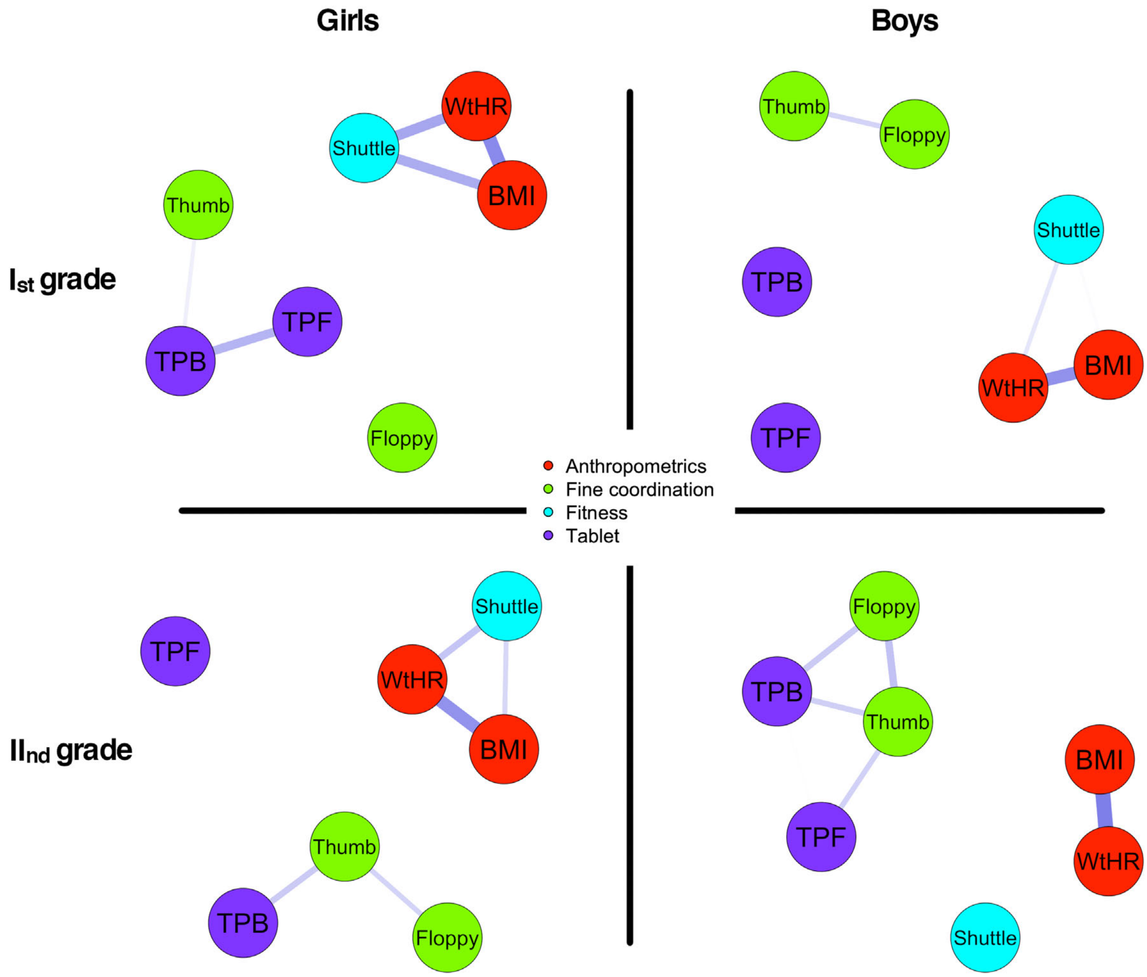

FIGURE 4 Network plots split by gender and school grade. The drawings reflect the strength, the closeness, and the clustering of the variables. The bolder the line, the higher the weight of the correlation between nodes. Nodes of the same colors belong to the same group, according to clustering measures of the analysis. Nodes are positioned in space using the Fruchterman-Reingold algorithm, based on the strength of connections. *TPB*: Tablet Performance Best; *TPF*: Tablet Performance Fast; BMI: Body mass index; WtHR: Waist-to-height ratio

We then ran the networks split by gender and age which revealed different models for boys and girls, see Figure 4. Considering the size of subsamples, we run this model without the aim to infer results, but to provide pilot evidence to be possibly confirmed by ad hoc designed studies.

The Shuttle, WtHR, and BMI were strongly linked in girls of both grades, but only to some degree in the younger group of boys. Thumb and Floppy were more linked in second than in first grade in girls showing a growing network of fine motor skills, but in boys, thumb and floppy were linked in both grades. Moreover, in boys, the tablet parameters became linked with thumbs and floppy task showing a generalization of fine motor expertise extending to computers. In contrast, in the older grade of girls, fast tablet motions were not networked anymore.

4 | DISCUSSION

A structured analysis of various motor tasks provides a better understanding of the motor tasks. In this regard, network analyses allow going beyond the typical correlation analyses, thanks to centrality measures and clustering. We examined the important transition into school when fine motor skills become essential for learning how to write. We addressed the structured links between grapho-motor performances and other fine motor skills, speed and agility, anthropometrics, and self-perception of motor skills in early school-age children. Our result demonstrated that, first, grapho-motor skills varied between boys and girls and exhibited gender-related differences, second, that three clusters (namely, perceived competence, fitness, and fine motor skills) emerged from the network model, and third, that the interconnectedness of fine motor skills with other domains may change with age and gender during early school age.

4.1 | Fine motor skills, cognitive functions, and tasks

Our results showed that when the strategy to carry out the grapho-motor task was focused on accuracy, this reduced the speed of the graphical task which confirms the finding by Giammarco et al. (2016) (see also Lange-Küttner, 1998) who observed that the slower the speed, the better is the quality. The speed accuracy trade-off has been studied widely, with evidence also in graphic tasks for school age children (e.g., Smits-Engelsman et al., 2006). Looking at the underlying factors of increased accuracy, we refer to Simpson et al. (2017), who suggested that inhibition is the key ability that enables children to draw recognizable objects. Inhibition may be evoked, for instance, when stopping drawing a line of overlapping figures (hidden line elimination) (e.g., Chen & Holman, 1989; Lange-Küttner, 2000). This possible inhibition requirement was here particularly evident in boys, although further research should confirm this finding with a study designed to discriminate slow vs fast tasks. The reason can be found in the gender-based differences in visuo-motor integration. For instance, controlling oscillations in tracing performance varies in boys but not in girls (Giammarco et al., 2016; Tabatabaey-Mashadi et al., 2015). Drawing development also differs between boys and girls in the near-far conceptualization of pictorial space as boys drew silhouettes as they would be visible from afar, while girls focused on ornaments that could be seen close-up (Lange-Küttner, 2011).

We could prove that the development of fine motor skills varies in boys and girls showing gender and age-related clusters that added further learning-related evidence to the field of graphonomics and grapho-motor performances. Beyond the strong individual motivation in the aim of accomplishing the motor task, both strategy and adaptation to the velocity constraint were gender-related. Fine motor skills seemed to be already networked in girls at the beginning of school but became linked and generalized in boys in the second year supported the view that sex differences; this result should be considered to understand performance strategies and underlying motor, cognitive, and neuronal patterns. This showed how a task can be solved by the two genders with different strategies and may shed new understanding on development of competence (Lange-Küttner, 2017).

Indeed, also in the current study, strategy and performance on fine motor control tests were task-related. The link between the two tablet parameters and the two fine coordinative tests were only small and changed with regards to age and gender, as shown in the networks. This dynamic perspective was also shown by Snapp-Childs and colleagues who reported specific training effects to eliminate drawing performance differences between ages (7–8 vs 10–12-year old children) and different coordination skill levels (Snapp-Childs et al., 2015).

4.2 | Observed and perceived physical performances

Our results of *Shuttle* test were comparable to findings of the study of Kolimechkov et al. (2019). Instead, our participants' data were slightly worse on anthropometric indexes (Santomauro et al., 2017; WHO, 2007). In particular, the high percentage of children over the limits of overweight and health hazard may highlight an alarming situation for public health, with the need for better interventions. However, we found that even if our participants performed quite well on the Shuttle test, they could nevertheless have a poor anthropometric status. The moderate positive weights revealed by network analysis of Shuttle with both BMI and WtHR nevertheless support the call for policy approaches to improve anthropometric status as a modifiable factor to enhance physical fitness (Zaqout et al., 2016).

Notwithstanding the anthropometric status, our participants reported high values of perceived movement skills competence. Fine and gross motor skills, fitness performance and morpho-functional parameters represent necessary *modules* to be evaluated objectively in order to define developmental trajectories (Bondi, Di Sano, Verratti, et al., 2020). Assessment of perceived competence is a measure that integrates such evaluations from a subjective point of view and allows to focus physical education on the possible mismatch between objective and perceived skills. In our study, boys scored higher than girls on the object control sub-scale; this result agrees with the findings of Estevan et al. (2018) on Spanish children. However, this higher self-evaluation is not accompanied by better objective results: ours and other results (Flatters et al., 2014) showed that young girls perform better than young boys on manual skills. Further studies should therefore increase the knowledge about gender differences in the relationship between objective and subjective motor skills, the developmental course of these linkages, sports and social consequences and the related educational interventions. A careful examination of the alignment of the objective skills and children's subjective ratings will help to strengthen the knowledge on these topics. Beyond the subjective measures of perceived skills, further studies should address also some parameters of the biopsychosocial framework (Bortoli et al., 2018) and some parameters of personal feeling such as enjoyment in physical activity experiences (Carraro et al., 2008).

4.3 | Fine motor skills in children's development

We consider fine motor control as an emergent issue in the understanding of motor behavior for auxological (auxology is the science of human growth), educational and kinesiological studies. The wide range of expressions of motor control suggests considering all the related subdomains. The current study supports the argument of addressing the several fine motor skills, in addition to gross motor skills, for children.

Improvement of fine motor skills in children is specific to practice of fine motor skills, even in an education-oriented household (Suggate et al., 2017). However, fine motor coordination was demonstrated in two studies to be of more importance for math than for literacy because of the visual–spatial imagery required in both pictorial and mathematical space (Pitchford et al., 2016). Thus, one could predict that stimulation of fine motor skills may even be relevant for the improvement of higher cognitive skills in the prepubertal period. More attention should be directed toward this field, providing a wide range of different motor experiences. Although being a fundamental learning experience in the beginning of school when learning to write. Fine motor skills represent a fundamental learning experience in the beginning of school when learning to write. However, children rarely choose to use these skills in other learning contexts such as free play, independently of whether their fine motor skills are well, or less well developed (Marr et al., 2004). We should also take advantage by acquiring longitudinal track records of fine motor coordination data, in the same way as already reported for gross-motor coordination (Reikerås et al., 2017; Vandorpe et al., 2012). Thus, both higher attention on fine-coordinative skills in early education and implementation of gross-coordinative activities and evaluation need more articulated planning and organization of physical education, addressing motor control and learning as a whole.

Motor control also reflects gender differences in fine motor coordination through the developmental process. Reikerås et al. (2017) showed girls to have a more pronounced and anticipatory fine motor coordination than boys. Also Flatters et al. (2014) reported superior manual control abilities in prepubescent girls performing novel tasks. We contributed to the field showing that the relationship between fine motor coordination and other domains is different by age and gender in early school age. Both the clustering of nodes of fine motor control and the clustering of physical fitness with anthropometric measures were likely influenced by gender, as shown in the differential networks by the differences in both the nodes positioning and the weight of edges. This topic is worth further investigating with longitudinal studies and we thus suggest that the relationships between motor tasks themselves and other physical outcomes might follow gender-based development trajectories. Also training studies (van Abswoude et al., 2019) may be interesting to the emerging field of research in fine motor skills.

Cognition and motor skills are interrelated at the level of brain structure, supported by similar cortical neural substrates (Pangelinan et al., 2011). Therefore, further studies are needed to better characterize the relationships of morphological and neural connections with different coordinative domains, and the advantages of optimizing sensory–motor integration during precisely controlled hand movements to foster the learning of fine motor skills (Ose Askvik et al., 2020; van der Meer & van der Weel, 2017). Interesting findings may result from studies focused on evaluating differences based on handedness and asymmetries, as they have been shown to be related to the type of manual task exerted (Bondi, Prete, Malatesta, & Robazza, 2020; Bondi, Robazza, & Pietrangelo, 2020).

4.4 | Limitations

The study did not come without limitations, such as the absence of data about social background and academic performance. One other gap in the assessment may have been that we did not measure previous use of digital devices that might have affected fine motor skills (Petrigna et al., 2021). Thus, the results of the study recommend not only including fine motor skills in early school age research, but also studying them as a special cluster.

5 | CONCLUSIONS

Our network analysis revealed three specific clusters: perceived competence, fitness, and fine motor skills. Given the relative independence of these physical performance areas, we suggest focusing on these three clusters as separate areas in physical education. Fine motor skills deserve further consideration in early school age, since these skills are important in a variety of tasks like sorting objects, handwriting, and handling digital media. The latter has become even more urgent during distant learning in the Covid lockdowns. Digital devices represent fashionable and effective tools to be used under an educational perspective; in remote teaching times, teaching and evaluation of academic homework inevitably require digital devices for monitoring and developing children's fine motor skills. Whether learning to write and thus increased fine motor control influences manual dominance is still an open question and further studies should provide clear insights.

Motor development can be interpreted in the paradigm of Dynamic System Theory (Smith & Thelen, 2003): person, task, and environment interact dynamically and critical changes in one or more subsystems can produce improvements in the resulting performance. From this perspective, the human movement system is a complex network of subsystems consisting of a plethora of interacting components (Glazier et al., 2003). The constraint of repetition in task-specific practice greatly enhances related skills and has more or less potential to be transferred to other skills. Even a slight change in one component of the dynamic system can lead to reorganization of structure and developmental change (Smith & Thelen, 2003). Therefore, both interventions and evaluations need to be carefully and finely tuned.

Specific evidence of several motor tests can lead to a proposal of "sentinels" for early identification of various neural and motor deficits. Network research provides an effective framework for discussing fine and gross motor skills during developmental age; network models can aid better modeling of motor tasks and design of smart classrooms, while providing insights into novel interactive technologies.

AUTHOR CONTRIBUTIONS

Danilo Bondi: Conceptualization (lead); formal analysis (lead); investigation (lead); methodology (lead); resources (supporting); visualization (lead); writing – original draft (lead); writing – review and editing (equal). **Claudio Robazza:** Conceptualization (supporting); methodology (supporting); project administration (equal); resources (lead); supervision (lead); writing – original draft (supporting); writing – review and editing (equal). **Christiane Lange-Küttner:** Supervision (supporting); writing – original draft (equal); writing – review and editing (lead). **Tiziana Pietrangelo:** Conceptualization (equal); funding acquisition (lead); investigation (supporting); methodology (supporting); project administration (equal); resources (supporting); supervision (lead); writing – original draft (supporting); writing – review and editing (supporting).

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CONFLICT OF INTEREST

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

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

ORCID

Danilo Bondi https://orcid.org/0000-0003-1911-3606

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