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ORIGINAL CONTRIBUTION

Developmental trajectories of motor skills during the preschool period

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Abstract
Children with developmental coordination disorder also manifest difficulties in non-motor domains (attentional, emotional, behavioral and socialization skills). Longitudinal studies can help disentangle the complex relationships between the development of motor skills and other cognitive domains. This study aims to examine the contribution of early cognitive factors to changes in motor skills during the preschool period. Children ($N=1144$) from the EDEN mother–child cohort were assessed for motor skills with the Copy Design task (NEPSY battery) and the parent-rated Ages and Stages Questionnaire (fine and gross motor skills scores) at ages 3 and 5–6 years. At 3 years, language skills were evaluated using tests from the NEPSY and ELOLA batteries. Emotional problems, conduct problems, inattention and hyperactivity symptoms, peer relationships and pro-social behavior were assessed with the Strengths and Difficulties Questionnaire (SDQ) also at 3 years. Linear and logistic regression models were performed to examine whether positive and negative changes in motor skills between 3 and 5–6 years are associated with specific cognitive skills at 3 years, while adjusting for a broad range of pre- and postnatal environmental factors. In the linear regression model, the SDQ Inattention symptoms score at 3 years was associated with negative changes in motor skills (standardized $\beta=-0.09$, SD $=0.03$, p value $=0.007$) and language skills at 3 years were associated with positive changes in motor skills (standardized $\beta=0.05$, SD $=0.02$, p value $=0.041$) during the preschool period. In logistic regression models, the SDQ Inattention symptoms score at 3 years was associated with a higher likelihood of a declining trajectory of motor skills (OR [95% CI] = 1.37 [1.02–1.84]). A higher language skills score at 3 years was associated with an increased likelihood of a resilient trajectory (1.67 [1.17–2.39]). This study provides a better understanding of the natural history of developmental coordination delays by identifying cognitive factors that predict changes in motor skills between the ages of 3 and 5–6 years.

Keywords Cohort studies · Longitudinal analysis · Preschool children · Motor skills · ADHD · Language

Introduction

Developmental Coordination Disorder (DCD) is a neurodevelopmental disorder that substantially hampers academic achievement [1, 2]. DCD is characterized by deficits in the acquisition and execution of coordinated motor skills and is marked by clumsiness and slowness or inaccuracy of performance of motor skills that cause interference with daily activities. This disorder concerns 2% to 6% of children in primary school [1, 3]. As for all neurodevelopmental disorders, this disorder rarely appears in isolation [4, 5]. Indeed, cross-sectional studies have consistently reported that other neurodevelopmental disorders (e.g., Attention Deficit Hyperactivity Disorder [ADHD] [6–8], Autism Spectrum Disorder [ASD] [9–11], speech and language disorders [12–15]) or difficulties in various cognitive domains [3], such as language [13, 16–19], attentional [6, 20–22], emotional, behavioral and socialization skills [23] are frequently associated with a deficit in motor skills. However, the available data were mostly based on cross-sectional studies which, unlike longitudinal studies, are not well suited to determine the temporal sequence across these cognitive domains [24].

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The frequent co-occurrence of DCD with other developmental disorders (or symptoms) may result from shared etiological factors. Indeed, several environmental (e.g., preterm birth [25, 26]) and genetic factors (e.g., Turner syndrome [27]) are known to be common to several neurodevelopmental disorders. At a neuropsychological level, cognitive deficits (e.g., mnemonic skills (short-term, working and long-term memories) or executive functions [28–30]) may directly affect the development of several cognitive domains (e.g., motor, attentional, language, emotional, behavioral and socialization skills). An important complementary hypothesis to explain the frequent co-occurrence of DCD with other developmental disorders would be that performances in non-motor domains might substantially influence the development of motor skills. However, to our knowledge, few longitudinal studies have investigated the influence of early language, attentional, emotional, behavioral and socialization skills on developmental trajectories of motor skills during the preschool period (except [24], which examined solely the influence of early language skills). In addition, most prior studies that have examined this issue did not combine information from neuropsychological tests and parental questionnaires. A better knowledge of the ways in which different cognitive domains interact with each other longitudinally during the preschool period is thus a crucial first step to improve our understanding of etiopathogenic factors of neurodevelopmental disorders.

To fill this gap in our knowledge, we used a linear regression approach on a large dataset to determine whether non-motor cognitive skills at 3 years are associated with specific changes in motor skills from 3 to 5–6 years of age. We also conducted logistic regression models to identify the specific cognitive skills at 3 years that are associated with a declining trajectory of motor skills between 3 and 5–6 years, and those that are associated with a resilient trajectory. Based on prior research, we hypothesize that non-motor cognitive domains may influence the implicit and/or explicit memory processes of motor learning. Better language skills may facilitate the explicit learning of motor skills [24]. Moreover, attentional, emotional, behavioral difficulties may affect the encoding, storage and/or retrieval of sensorimotor schemas [31, 32]. Non-motor skills, such as behavioral and socialization difficulties, may also lead to a reduction in physical activity [33, 34] which will eventually result in even fewer opportunities for motor learning [35].

Materials and methods

Study design

We used data from the EDEN (*Etude des Déterminants pré- et postnatals précoces du développement et de la santé de l'Enfant*) prospective mother–child cohort study [36]. The primary aim of the EDEN cohort is to identify prenatal and early postnatal nutritional, environmental and social determinants of children's health and development. Participants were recruited between 2003 and 2006 among pregnant women followed in university maternities of Poitiers and Nancy, France. Exclusion criteria included history of diabetes, twin pregnancies, intention to deliver outside the university hospital or to move out of the study region within the next 3 years, and inability to speak French. Compared to the 2003 National Perinatal Survey (ENP) representative of women who delivered in France [37], women participating in the EDEN study ($N=2002$) had similar sociodemographic characteristics except for educational background (53.6% had a high-school diploma versus 42.6% in the ENP survey) and employment level (73.1% were employed during pregnancy versus 66.0% in the ENP survey) [38]. The study was approved by the Ethical Research Committee (*Comité Consultatif de Protection des Personnes dans la Recherche Biomédicale*) of Bicêtre Hospital and by the Data Protection Authority (*Commission Nationale de l'Informatique et des Libertés*). Informed written consent was obtained from parents for themselves at the time of enrollment and for the child after delivery.

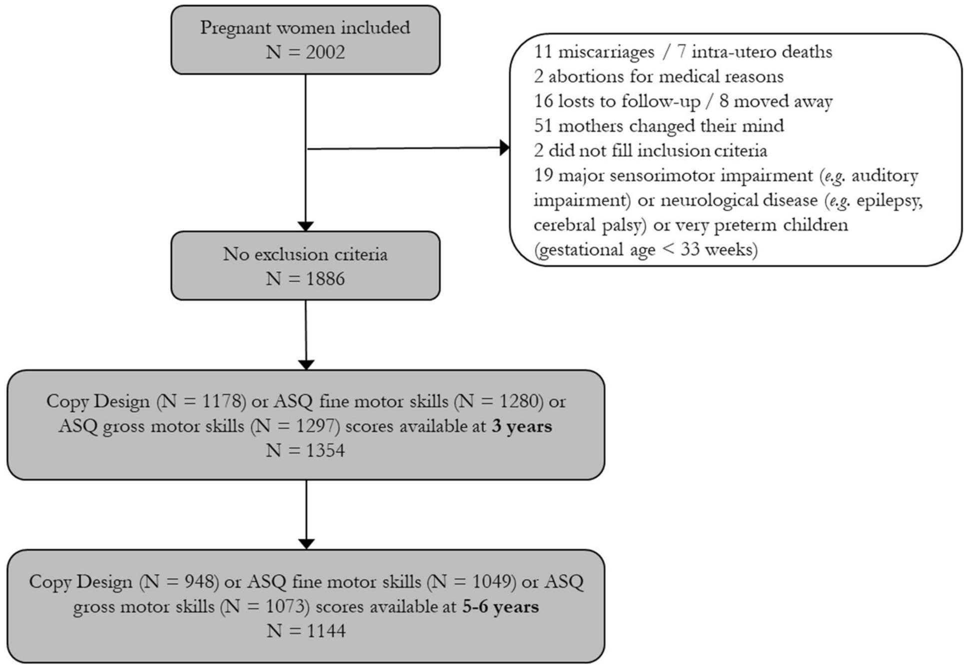
Participants

Among the 2002 pregnant women included in the EDEN study, 1907 children were followed up after birth, as described in detail elsewhere [36]. At the age of 3 years, 1354 children were assessed using the Ages and Stages Questionnaire (ASQ) and/or the Copy Design task (NEPSY) [39, 40] (See Flowchart on Fig. 1). Among them, 1144 were re-assessed at 5–6 years. Compared to children assessed at 3 years only ($N=210$; Table 1), those with repeated assessment had better fine motor skills (ASQ fine motor skills score) at 3 years and differed with regard to several covariates, such as family income, level of parental education, smoking during pregnancy, reflecting a typical selection bias in favor of children with lower risk factors and better development.

Measures

Motor skills were assessed at 3 and 5–6 years with the same parental questionnaires and neuropsychological tests. Other cognitive skills evaluated at 3 years were also explored using parental questionnaires (attentional, emotional, behavioral and socialization skills) and neuropsychological tests (language skills).

Fig. 1 Flowchart



Motor skills at 3 and 5–6 years

Parental questionnaire: ages and stages questionnaire (ASQ) Development was investigated at 3 years and 5–6 years of age using the second French edition of the ASQ [41]. This is a parent completed assessment including 5 domains of development (communication, gross motor, fine motor, problem solving, and personal-social) with 6 questions in each domain. For each question, there is a choice of three responses: "Yes", "Sometimes", or "Not yet", which are scored as 10, 5, or 0, respectively. In the present study, we considered the ASQ fine and gross motor skills scores.

Neuropsychological tests: copy design task Trained psychologists in the two study centers assessed children's cognitive skills at 3 years (mean ± SD: 38.0 ± 0.8 months) and between 5 and 6 years (67.8 ± 1.8 months). The Copy Design task (NEPSY) [39, 40] was scored as the number of designs correctly copied (18 items; each item rated from 0 to 4). The designs progressively increase in complexity (vertical line, horizontal line, circle, etc.). This scale measures fine motor skills as well as visual–motor integration [39].

Cognitive predictors at 3 years

Language skills

- *Semantic fluency* (ELOLA) [42] was assessed by the sum of (a) the number of animals and (b) the number of objects named in 1 min by the child. This test taps expressive vocabulary and lexical retrieval.
- *Word and nonword repetition* (ELOLA) was assessed by the number of words (6 items) and nonwords (6 items) repeated correctly. This test taps phonological processing and verbal short-term memory.
- *Sentence repetition* (NEPSY) was ascertained by the number of sentences of increasing complexity and length repeated correctly (17 items, e.g., "sleep well"). This test taps verbal short-term memory and syntactic skills.
- *Picture naming* (ELOLA) was assessed by the number of pictures named correctly (10 items, e.g., "horse"). This test taps expressive vocabulary.
- *Comprehension of instructions* (NEPSY), a sentence comprehension task, was assessed by the number of correct answers obtained by pointing at one of 8 pictures (13 items, e.g., "show me a large rabbit"). This subtest is designed to assess the ability to receive, process, and execute oral instructions of increasing syntactic complexity.

Since an exploratory factor analysis of these 5 variables yielded a single factor (first factor eigenvalue = 2.6; second factor eigenvalue = 0.7) explaining 53% of the total variance and with similar loadings on all variables (Semantic fluency = 0.52, Word and nonword repetition = 0.50, Sentence comprehension = 0.53, Sentence repetition = 0.57, Picture naming = 0.52), a single language score representing language skills at 3 years was calculated as the mean of the five standardized scores [43].

Emotional, behavioral and social problems assessment The Strengths and Difficulties Questionnaire (SDQ) [44–46] was

Table 1 Summary statistics of participants included in the analyses and excluded because of missing data on motor skills at 5–6 years

	Included Motor skills at 3 and 5–6 years available *N* = 1144 Mean (SD) (or %)	Excluded Motor skills at 3 years available but missing at 5–6 years *N* = 210 Mean (SD) (or %)	*p* values
Motor skills			
At 3 years			
Copy Design	9.6 (2.3)	9.5 (2.6)	0.7
ASQ fine motor skills	52.0 (11.2)	49.0 (14.2)	0.002
ASQ gross motor skills	55.1 (7.6)	54.9 (7.8)	0.7
At 5–6 years			
Copy Design	17.1 (2.9)	–	–
ASQ fine motor skills	57.6 (4.4)	–	–
ASQ gross motor skills	57.5 (5.3)	–	–
Cognitive tests			
At 3 years			
SDQ dimensions			
Emotional symptoms score	6.8 (1.6)	6.9 (1.7)	0.2
Conduct problems score	6.2 (2.0)	6.3 (1.9)	0.3
Hyperactivity/inattention symptoms score	4.4 (2.3)	4.7 (2.1)	0.087
Peer relationship problems score	2.5 (1.5)	2.6 (1.6)	0.2
Prosocial behavior score	12.7 (1.7)	12.7 (1.8)	0.8
Language tests			
Semantic fluency (ELOLA)*	−0.01 (0.84)	0.05 (0.9)	0.4
Word and nonword repetition (ELOLA)*	0.01 (0.94)	−0.07 (0.9)	0.3
Sentence repetition (NEPSY)	7.2 (3.3)	7.1 (3.0)	0.7
Picture naming (ELOLA)	7.0 (1.9)	6.8 (1.9)	0.3
Comprehension of instructions (NEPSY)	8.5 (3.0)	8.3 (3.0)	0.4
Pre- and postnatal environmental factors			
Male (vs. female), %	53.4	44.7	0.022
Gestational age (weeks)	39.3 (1.7)	39.3 (1.6)	0.5
Birth weight (kg)	3.29 (0.50)	3.26 (0.46)	0.4
Maternal age at birth of child (years)	26.6 (4.6)	28.4 (5.0)	< 0.001
Paternal age at birth of child (years)	32.3 (5.6)	31.9 (6.3)	0.3
Tobacco consumption during pregnancy (vs. no), %	21.2	30.5	0.003
Alcohol during pregnancy (drinks/week)	0.54 (1.42)	0.50 (1.67)	0.7
Breastfeeding initiation (vs. no), %	72.6	74.3	0.6
Maternal depression after birth (vs. no), %	32.5	31.4	0.7
Household income (k€)	2.75 (0.99)	2.55 (1.07)	0.010
Parental education (years)	13.7 (2.3)	13.2 (2.3)	0.002
Caretaker at 2 years (mother or family vs. nursery or other), %	37.7	49.5	0.001
Single-parent household (vs. no), %	7.0	11.3	0
Score for family stimulation at 2 years	3.3 (0.5)	3.3 (0.5)	0.6
Score for family stimulation at 3 years	2.8 (0.6)	2.8 (0.6)	0.3
Score for family stimulation at 5–6 years	17.3 (2.2)	17.0 (2.2)	0.7
Older sibling (vs. no), %	53.2	54.6	0.7
Younger sibling at 5–6 years (vs. no), %	40.3	40.0	0.8
School attendance at the time of testing (at 3 years) (vs. no), %	64.2	65.0	0.8
Recruitment center (Nancy), %	43.8	59.5	< 0.001

**Z* scores. In our sample of analysis, 5.7% were born preterm (gestational age < 37 weeks) used to measure emotional and behavioral problems when children were aged 3 years. The SDQ is a 25-item scale comprising five scores covering emotional problems (fears, worries, misery, nervousness and somatic symptoms), conduct problems (tantrums, obedience, fighting, lying and stealing), inattention (inability to concentrate, distractibility and impulsivity) and hyperactivity symptoms (restlessness, fidgeting), peer relationships (popularity, victimization, isolation, friendship and the ability to relate to children as compared to adults), and pro-social behavior (consideration of others, ability to share, kindness to younger children, helpfulness to other children when distressed and willingness to comfort others). Answer options for each item are: 'Not true' 'Somewhat true' or 'Very true', scored 0, 1 or 2, yielding a total score ranging from 0 to 10 for each subscale. Higher scores represent worse functioning except for prosocial behavior. The five-factor structure of the SDQ at 3 has been supported by some studies [47] but not all [48]. In our models, we created two different scores for inattention and hyperactivity symptoms since an exploratory factor analysis of the 5 symptoms of inattention/hyperactivity yields a two-factor solution (first factor eigenvalue = 2.4; second factor eigenvalue = 1.0; third factor = 0.7) (see supplementary Table 1). In the present data, Cronbach's alphas for each SDQ scale at 3 years were: 0.55 for emotional symptoms, 0.69 for conduct problems, 0.63 for inattention symptoms, 0.76 for hyperactivity symptoms, 0.48 for peer relationship problems and 0.60 for prosocial behavior.

Other variables Sex, gestational age and birth weight were collected from obstetrical records. Smoking status and alcohol consumption during pregnancy (units/week) were determined from the questionnaires filled by the mother during pregnancy and at delivery. Both parents provided data regarding their age at the child's birth, family income, educational level and single-parent household. The average level of parental education and household income (k€/months) was used in the analyses. Mothers completed questionnaires on partial or exclusive breastfeeding (breastfeeding initiation) [49]. We assessed maternal depression after birth with the Edinburgh Postnatal Depression Scale at 4, 8 and 12 months (a cutoff of 13 was used to define depression [50, 51]) and with the CES-D at 3 and 5 years following delivery (a cutoff of 16 was used to define depression [52, 53]). When the child was 2 years, mothers reported the main caretaker mother or family (e.g., father, grandparents) and nursery and others (e.g., child minder). At child's age 2 and 3 years, maternal cognitive stimulation of the child at home was assessed by a questionnaire completed by the mother and evaluating the weekly frequency of 8 activities (e.g., storytelling, singing, drawing, etc.). When the child was 5–6 years, cognitive stimulation at home was assessed by a psychologist using three subscales of the Home Observation for the Measurement of the Environment Scale: language stimulation, academic stimulation, and variety of experimentations [54, 55]. Higher scores represent greater cognitive stimulation and emotional support. The presence of older siblings, the presence of younger siblings at 5–6 years and the child's entry to pre-elementary school at the time of testing (at 3 years) were also considered in the analyses.

Statistical analyses

First, we performed a linear regression model with motor skills at 5–6 years (calculated as the mean of age-adjusted Copy Design, ASQ fine motor skills and ASQ gross motor skills scores at 5–6 years) as dependent variable and motor skills at 3 years (calculated as the mean of age-adjusted Copy Design, ASQ fine motor skills and ASQ gross motor skills scores at 3 years) and other cognitive skills at 3 years as independent variables, while adjusting for pre- and postnatal environmental factors. The same models were also conducted using either the Copy Design scores or the ASQ fine motor skills scores or the ASQ gross motor skills scores to determine whether our results were consistent across all motor skills measurements.

Secondly, we performed logistic regression models to identify the specific cognitive skills at 3 years that are associated with a declining trajectory of motor skills between 3 and 5–6 years and the specific cognitive skills at 3 years that are associated with a resilient trajectory. At 3 and 5–6 years, children were considered to have a deficit in motor skills if their score (age-adjusted) was below the 10th percentile on the Copy Design score and/or the ASQ fine motor skills score and/or the ASQ gross motor skills score. Four patterns of motor skills' change were then determined:

- Typical motor skills (Typical group): scoring within normal limits at both 3 and 5–6 years.
- Resilient motor skills (Resilient group): scoring within normal limits at 5–6 years only.
- Declining motor skills (Declining group): scoring within normal limits at 3 years only.
- Consistently low motor skills (Consistently low group): scoring within normal limits neither at 3 years nor at 5–6 years.

Logistic regression models were performed to examine whether specific cognitive skills at 3 years were associated with changes in motor skills between 3 and 5–6 years (i.e., "Declining group" compared to "Typical group" (Declining trajectory model) and "Resilient group" compared to "Consistently low group" (Resilient trajectory model)), while adjusting for pre- and postnatal environmental factors.

We used multiple imputation to handle the missing data in our analysis [56, 57]. Because sex may influence the temporal relationships between cognitive domains, models were reproduced these analyses while stratifying on sex. All statistical analyses were performed using SAS 9.2 software (SAS Institute, Cary, NC, USA). Given the exploratory nature of this study, we did not correct for multiple comparisons.

Results

The clinical characteristics of the participants included in our analyses are presented in Table 1. In the linear regression model, the SDQ Inattention symptoms score at 3 years was associated with negative changes in motor skills ($\beta = -0.09$, SD = 0.03, p value = 0.007) and language skills at 3 years were associated with positive changes in motor skills ($\beta = 0.05$, SD = 0.02, p value = 0.041) during the preschool period. Moreover, family household income and cognitive stimulation of the child at home at 5–6 years were associated with positive changes in motor skills (Table 2). All language tests at 3 years were positively associated with motor skills at 5–6 years, yet only the regression parameter of Comprehension of instructions ($\beta = 0.02$, SD = 0.01, p value = 0.002) was statistically significant, while that of Picture naming was marginally so ($\beta = 0.04$, SD = 0.02, p value = 0.070). The Copy Design, ASQ fine and gross motor skills scores were moderately correlated at 3 (r(Copy Design and ASQ fine) = 0.36; r(Copy Design and ASQ gross) = 0.20; r(ASQ fine and ASQ gross) = 0.31) and 5 years (r(Copy Design and ASQ fine) = 0.32; r(Copy Design and ASQ gross) = 0.19; r(ASQ fine and ASQ gross) = 0.32). Children whose motor skill scores were missing for at least one measurement at 3 and 5–6 years ($N = 71$; Copy Design Task missing [$N = 56$]; ASQ fine motor skills subscore missing [$N = 14$]; ASQ gross motor skills subscore missing [$N = 8$]) had parents with higher education (p value = 0.034) and income (p value = 0.015) and they also had lower cognitive stimulation at 5–6 years (p value = 0.028) than those whose scores were all available at 3 or 5–6 years [$N = 1073$]. When reproducing this analysis using either the Copy Design scores (in a subsample of 871 children) or the ASQ fine motor skills scores (in a subsample of 1012 children) or the ASQ gross motor skills scores (in a subsample of 1042 children), we found similar results (see supplementary Table 2). When reproducing these analyses separately in boys ($N = 611$) and girls ($N = 533$), results were close to those obtained in the total sample (see linear regression models in supplementary Tables 3 and 4). Indeed, SDQ Inattention symptoms and language skills at 3 years were associated with changes in motor skills in all models of both sexes (the regression parameters were not statistically significant in the linear regression models—except for SDQ Inattention symptoms at 3 years in girls).

In our sample of 1144 children for whom motor skills at 3 and 5–6 years were available, 754 children were in the Typical group, 142 children in the Resilient group, 141 children in the Declining group and 107 children in the Consistently low group (see Table 3 and Fig. 2). Compared to children in the Typical group, the SDQ Inattention symptoms score (OR [IC-95%]: 1.37 [1.02–1.84]) and cognitive stimulation of the child at home at 5–6 years predicted children's odds of being in the Declining group (Table 4). Children's language skills score at 3 years (1.67 [1.17–2.39]) and the recruitment center predicted children's odds of being in the Resilient group, rather than in the Consistently low group. All language tests at 3 years were positively associated with children's odds of being in the Resilient trajectory, yet only the OR associated with word and nonword repetition was not statistically significant.

Discussion

Main findings

Using data from the EDEN prospective mother–child cohort, our study examined whether trajectories of motor skills during the preschool period are predicted by early performance in other cognitive domains (language, attentional, emotional, behavioral and socialization skills).

Early symptoms of inattention as well as language skills were negatively and positively associated (respectively) with changes in motor skills during the preschool period. Moreover, early symptoms of inattention were found to be positively associated with a trajectory of declining difficulties in motor skills, while early language skills were positively associated with the resilient trajectory. Overall, these findings suggest that children's cognitive characteristics predict motor skills longitudinally and should be assessed when aiming to predict the ways in which children's motor skills are likely to evolve over time.

Association of symptoms of inattention with the declining trajectory of motor skills

Previous cross-sectional studies have established that most children with ADHD frequently exhibit difficulties in motor skills and about 50% meet criteria for DCD [6–8, 58]. Children with ADHD are also less proficient in visuomotor integration [59, 60]. Moreover, clinical trials have found an improvement in motor skills among children with ADHD receiving treatment (mostly methylphenidate) [8, 61], even shortly after the introduction of this treatment [62]. Our longitudinal study indicates that symptoms of inattention may influence the development of motor skills during the preschool period. Symptoms of inattention may affect the

Table 2 Linear regression models of the developmental trajectories of motor skills

	Motor skills score at 5–6 years[a] $N = 1144$		
	β	SD	p value
Motor skills at 3 years			
Motor skills[a]	**0.37**	**0.03**	**< 0.001**
Cognitive tests			
At 3 years			
SDQ dimensions			
Emotional symptoms score	− 0.02	0.02	0.387
Conduct problems score	− 0.01	0.02	0.776
Hyperactivity symptoms score	0.00	0.03	0.965
Inattention symptoms score	**− 0.09**	**0.03**	**0.007**
Peer relationship problems score	0.00	0.02	0.834
Prosocial behavior score	0.03	0.02	0.205
Language score at 3 years	**0.05**	**0.02**	**0.041**
Semantic fluency (ELOLA)[b]	*0.00*	*0.02*	*0.859*
Word and nonword repetition (ELOLA)[b]	*0.01*	*0.01*	*0.540*
Sentence repetition (NEPSY)[b]	*0.00*	*0.02*	*0.939*
Picture naming (ELOLA)[b]	*0.04*	*0.02*	*0.070*
Comprehension of instructions (NEPSY)[b]	***0.02***	***0.01***	***0.002***
Pre- and postnatal environmental factors			
Male (vs. female)	0.00	0.04	0.972
Gestational age	0.03	0.03	0.240
Birth weight	0.00	0.03	0.932
Maternal age at birth of child	0.01	0.03	0.793
Paternal age at birth of child	0.00	0.00	0.766
Tobacco consumption during pregnancy (vs. no)	0.04	0.05	0.409
Alcohol during pregnancy	0.01	0.02	0.722
Breastfeeding initiation (vs. no)	− 0.01	0.05	0.916
Maternal depression after birth (vs. no)	0.01	0.05	0.803
Household income	**0.08**	**0.03**	**0.005**
Parental education	− 0.01	0.03	0.688
Caretaker at 2 years (mother or family vs. nursery or other)	− 0.05	0.05	0.294
Single-parent household (vs. no)	− 0.02	0.08	0.802
Score for family stimulation at 2 years	0.05	0.02	0.054
Score for family stimulation at 3 years	− 0.02	0.02	0.317
Score for family stimulation at 5–6 years	**0.05**	**0.02**	**0.021**
Older sibling (vs. no)	0.01	0.05	0.789
Younger sibling at 5–6 years (vs. no)	0.03	0.05	0.560
School attendance at the time of testing (at 3 years) (vs. no)	− 0.01	0.06	0.817
Recruitment center (Poitiers vs. Nancy)	− 0.03	0.05	0.579

All continuous variables were standardized (mean = 0; SD = 1) for better interpretability. In bold: $p < 0.05$

[a]Calculated as the mean of Copy Design, ASQ fine and ASQ gross motor skills scores

[b]Regression parameters were estimated in separated models for each language test at 3 years. These models were performed if language score at 3 years was significantly associated with positive and negative changes in motor skills between 3 and 5–6 years

encoding, storage and/or retrieval of sensorimotor schemas, as well as the learning processes leading to the automatization of motor skills. Indeed, motor learning notably relies on attentional skills, short-term/working memory and executive functions, which are known to be affected in most ADHD children. Future longitudinal studies could examine these potential mediating mechanisms. Prior imaging studies have suggested the existence of sex differences in ADHD

Table 3 Summary statistics of the 4 developmental trajectories of motor skills

	Typical motor skills (*N* = 754)	Resilient motor skills (*N* = 142)	Declining motor skills (*N* = 141)	Consistently low motor skills (*N* = 107)
	Mean (SD) (or %)	Mean (SD) (or %)	Mean (SD) (or %)	Mean (SD) (or %)
Motor skills				
At 3 years				
Copy design	10.3 (1.6)	7.6 (2.8)	9.8 (1.7)	6.9 (3.0)
ASQ fine motor skills	55.9 (5.9)	41.9 (15.2)	52.7 (7.6)	32.7 (15.7)
ASQ gross motor skills	57.7 (3.9)	47.9 (10.8)	56.9 (4.4)	45.4 (10.3)
At 5–6 years				
Copy design	18.0 (2.3)	17.2 (2.2)	14.7 (2.9)	14.1 (3.4)
ASQ fine motor skills	59.0 (2.1)	58.6 (2.3)	53.6 (5.8)	52.2 (7.5)
ASQ gross motor skills	59.1 (2.3)	58.6 (2.7)	53.8 (7.2)	49.9 (9.6)
Cognitive tests				
At 3 years				
SDQ dimensions				
Emotional symptoms score	6.7 (1.6)	6.9 (1.6)	6.7 (1.5)	7.1 (2.1)
Conduct problems score	6.0 (2.0)	6.5 (2.0)	6.3 (2.1)	6.7 (2.2)
Hyperactivity/inattention symptoms score	4.1 (2.1)	4.8 (2.5)	5.0 (2.5)	5.3 (2.2)
Peer relationship problems score	2.3 (1.4)	2.8 (1.6)	2.4 (1.5)	3.1 (1.7)
Prosocial behavior score	12.9 (1.6)	12.5 (1.7)	12.7 (1.6)	11.8 (2.0)
Language tests				
Semantic fluency (ELOLA)*	0.08 (0.83)	−0.22 (0.88)	0.01 (0.79)	−0.56 (0.68)
Word and nonword repetition (ELOLA)*	0.16 (0.87)	−0.30 (0.97)	−0.14 (1.00)	−0.47 (1.04)
Sentence repetition (NEPSY)	7.6 (3.2)	6.5 (3.7)	7.0 (3.1)	5.4 (3.6)
Picture naming (ELOLA)	7.3 (1.6)	6.3 (2.0)	7.1 (1.9)	5.4 (2.7)
Comprehension of instructions (NEPSY)	9.0 (2.8)	7.6 (3.1)	8.3 (2.9)	6.5 (3.1)
Language score	1.52 (0.90)	1.10 (1.01)	1.30 (0.91)	0.65 (0.99)
Pre- and postnatal environmental factors				
Male (vs. female), %	50.1	63.4	51.8	65.4
Gestational age (weeks)	39.4 (1.5)	39.1 (2.0)	39.1 (1.8)	38.9 (2.3)
Birth weight (kg)	3.3 (0.5)	3.3 (0.6)	3.3 (0.5)	3.2 (0.7)
Maternal age at birth of child (years)	29.7 (4.6)	29.8 (4.8)	29.6 (4.4)	28.8 (4.6)
Paternal age at birth of child (years)	32.4 (5.6)	32.6 (6.2)	32.2 (5.6)	32.1 (5.0)
Tobacco consumption during pregnancy (vs. no), %	19.5	26.8	19.9	27.1
Alcohol during pregnancy (drinks/week)	0.54 (1.51)	0.53 (0.88)	0.40 (0.75)	0.74 (1.96)
Breastfeeding initiation (vs. no), %	75.7	65.5	73.1	59.8
Maternal depression after birth (vs. no), %	30.0	37.3	35.5	40.2
Household income (k€)	2.84 (0.98)	2.77 (1.11)	2.58 (0.89)	2.32 (0.88)
Parental education (years)	14.0 (2.3)	13.5 (2.2)	13.4 (2.3)	12.5 (2.1)
Caretaker at 2 years (mother or family vs. nursery or other), %	35.5	39.4	40.4	46.7
Single-parent household (vs. no), %	8.0	3.7	5.1	6.8
Score for family stimulation at 2 years	3.3 (0.5)	3.3 (0.5)	3.3 (0.5)	3.3 (0.5)
Score for family stimulation at 3 years	2.7 (0.6)	2.7 (0.6)	2.7 (0.7)	2.8 (0.6)
Score for family stimulation at 5–6 years	17.5 (2.1)	17.0 (2.5)	16.9 (2.4)	16.6 (2.7)
Older sibling (vs. no), %	52.9	57.0	58.9	47.2
Younger sibling at 5–6 years (vs. no), %	42.7	28.2	39.0	41.1
School attendance at the time of testing (at 3 years) (vs. no), %	63.7	61.1	69.3	64.3

Table 3 (continued)

	Typical motor skills ($N=754$)	Resilient motor skills ($N=142$)	Declining motor skills ($N=141$)	Consistently low motor skills ($N=107$)
	Mean (SD) (or %)	Mean (SD) (or %)	Mean (SD) (or %)	Mean (SD) (or %)
Recruitment center (Nancy), %	45.1	35.2	46.8	42.1

*Z scores

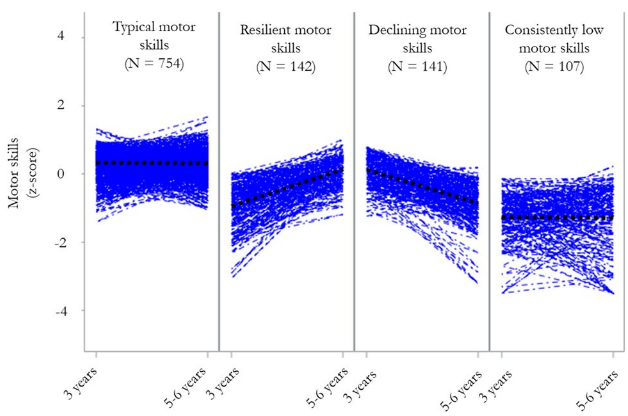


Fig. 2 Motor skills trajectories between 3 and 5–6 years

(sex-based differences in cortical morphology of functional subdivisions of the frontal lobe) [63, 64], possibly contributing to the greater motor impairment and more neurological soft signs observed in boys with ADHD [63]. However, in our study, we found no sexual dimorphism with regard to the association of symptoms of inattention with changes in motor skills during the preschool period.

Association of language skills with the resilient trajectory of motor skills

Cross-sectional studies have reported that language impairments [13, 16–19] and speech and language disorders [12–15]) are frequently associated with deficits in motor skills. Our results indicate that children's early deficits in trajectories of motor skills are substantially influenced by their language skills. Among children with deficits in motor skills, learning motor skills could be facilitated through verbal instruction, whereas implicit learning could be less efficient [65, 66]. This explanation is congruent with the type of rehabilitative interventions that are currently recommended for children with DCD, such as the Cognitive Orientation to Daily Occupational Performance approach (CO-OP) [67–69]. Indeed, the CO-OP is a cognitive motor-approach which aims to develop verbal self-interrogation, self-monitoring, self-observation and self-evaluation strategies. Future longitudinal studies should examine the mnemonic processes (implicit *versus* explicit) involved in motor learning in children with DCD.

We also found that with family household income was positively associated with children's changes in motor skills, and in particular with a higher likelihood of a resilient trajectory of motor skills. When children were aged 3, 4 and 5–6 years, parents completed a questionnaire assessing if their child had consulted a psychiatrist, a psychologist or an occupational therapist in the public or private sectors. The use of mental health services (between the ages of 3 to 5–6 years) was lower among children belonging to the resilient trajectory of motor skills (14.8%) than among those with a consistently low trajectory of motor skills (31.8%; p value $=0.002$). This result suggests that the influence of household income on children's odds of belonging to the resilient trajectory may not be explained by a better financial access to mental health services. To further investigate the effect of family household income on changes in motor skills, we performed the linear regression model separately in children with family household income below the median of the sample (low income) and those above the median (high income). In these supplementary analyses, we found that cognitive stimulation of the child at home at 5–6 years was positively associated with the likelihood of a resilient trajectory of motor skills in the subsample with low income ($\beta=0.07$ (SD $=0.04$); p value $=0.042$), but not in the subsample with high income ($\beta=0.02$ (SD $=0.03$); p value $=0.5$). These results suggest that cognitive stimulation may have a higher influence (interaction between household income and cognitive stimulation of the child at home at 5–6 years: p value $=0.13$) on changes in motor skills among children in families with low compared to those in families with high income.

Strengths and limitations

Strengths of our study include its longitudinal design with repeated assessments of children's fine motor skills and the use of validated tests and questionnaires to explore participants' motor and language skills. The Pearson correlation coefficients between the three measures at 3 years (mean $r=0.29$) and 5–6 years (mean $r=0.28$) were weak. Parental report that has been previously reported correlates only weakly with the objectively assessed motor skills [70].

Table 4 Logistic regression models of the developmental trajectories of motor skills

	Declining motor skills versus Typical motor skills			Resilient motor skills versus Consistently low motor skills		
	OR	IC 95%	*p* value	OR	IC 95%	*p* value
Cognitive tests						
At 3 years						
SDQ dimensions						
Emotional symptoms score	0.91	0.72–1.14	0.401	1.01	0.74–1.37	0.967
Conduct problems score	0.95	0.75–1.20	0.659	0.82	0.55–1.21	0.322
Hyperactivity symptoms score	1.11	0.86–1.43	0.414	1.36	0.90–2.06	0.149
Inattention symptoms score	**1.37**	**1.02–1.84**	**0.037**	0.98	0.58–1.65	0.934
Peer relationship problems score	1.19	0.96–1.49	0.114	1.16	0.84–1.61	0.365
Prosocial behavior score	0.99	0.79–1.24	0.909	**1.65**	**1.15–2.37**	**0.006**
Language score at 3 years	0.87	0.68–1.10	0.243	**1.67**	**1.17–2.39**	**0.005**
Semantic fluency (ELOLA)[a]				***1.36***	***1.05–1.75***	***0.019***
Word and nonword repetition (ELOLA)[a]				*1.11*	*0.94–1.32*	*0.206*
Sentence repetition (NEPSY)[a]				***1.35***	***1.02–1.78***	***0.034***
Picture naming (ELOLA)[a]				***1.39***	***1.06–1.82***	***0.019***
Comprehension of instructions (NEPSY)[a]				***1.14***	***1.02–1.28***	***0.021***
Pre- and postnatal environmental factors						
Male (vs. female)	0.97	0.85–1.26	0.727	1.16	0.60–1.25	0.434
Gestational age	0.90	0.70–1.15	0.399	1.03	0.72–1.48	0.856
Birth weight	0.94	0.72–1.22	0.633	0.94	0.64–1.38	0.755
Maternal age at birth of child	0.97	0.73–1.28	0.832	1.30	0.84–2.01	0.241
Paternal age at birth of child	1.00	0.95–1.05	0.904	0.96	0.89–1.04	0.306
Tobacco consumption during pregnancy (vs. no)	0.91	0.70–1.17	0.463	0.98	0.69–1.39	0.899
Alcohol during pregnancy	0.88	0.67–1.15	0.345	0.75	0.46–1.20	0.226
Breastfeeding initiation (vs. no)	0.99	0.78–1.24	0.907	0.84	0.59–1.22	0.365
Maternal depression after birth (vs. no)	1.11	0.90–1.37	0.337	1.18	0.84–1.66	0.350
Household income	0.81	0.61–1.08	0.150	1.47	0.95–2.26	0.081
Parental education	0.95	0.73–1.24	0.717	1.29	0.83–2.01	0.252
Caretaker at 2 years (mother or family vs. nursery or other)	0.99	0.79–1.23	0.900	0.85	0.61–1.20	0.362
Single-parent household (vs. no)	0.65	0.41–1.03	0.067	0.77	0.37–1.59	0.481
Score for family stimulation at 2 years	0.89	0.70–1.12	0.314	1.34	0.90–1.97	0.147
Score for family stimulation at 3 years	1.18	0.94–1.50	0.161	0.88	0.61–1.28	0.502
Score for family stimulation at 5–6 years	**0.79**	**0.62–0.99**	**0.045**	0.92	0.67–1.25	0.582
Older sibling (vs. no)	1.12	0.88–1.44	0.347	1.32	0.92–1.91	0.134
Younger sibling at 5–6 years (vs. no)	0.89	0.71–1.12	0.332	0.97	0.68–1.38	0.865
School attendance at the time of testing (at 3 years) (vs. no)	1.18	0.95–1.45	0.131	0.81	0.58–1.13	0.219
Recruitment center (Poitiers vs. Nancy)	1.00	0.80–1.27	0.966	**1.48**	**1.00–2.19**	**0.049**

All continuous variables were standardized (mean = 0; SD = 1) for better interpretability. In bold: $p < 0.05$

[a]Regression parameters were estimated in separated models for each language test at 3 years. These models were performed if language score at 3 years was significantly associated with positive and negative changes in motor skills between 3 and 5–6 years

Combining two sources of measurement (neuropsychological tests and parental questionnaires) of motor skills was thought to provide complementary information.

Our study has several limitations. First, developmental trajectories of children's motor skills, language and symptoms of inattention are complex and intertwined. Our analysis did not allow us to examine the reciprocal effects of motor skills on symptoms of inattention and language skills. Second, our study was not suited to examine the mediating mechanisms by which symptoms of inattention influence children's declining trajectory of motor skills, or children's language influences the odds of belonging to the resilient trajectory of motor skills. Third, symptoms of inattention were assessed using behavior rating scales completed by parents (SDQ) and could reflect reporting bias. Other sources of information, in particular preschool teacher's ratings of symptoms inattention, would have also been valuable. Indeed, the child's ability to attend and concentrate and remain at his/her desk or place is usually tested more accurately in preschool settings [71]. In addition, our score of inattention symptoms was based on a limited number of items. Further studies, measuring children's a wide range of symptoms of inattention through teachers' or other non-parental raters would be valuable. Fourth, multiple testing may have been responsible for type 1 error inflation. However, our results were significant after adjusting for a wide range of potential confounders and when using both a continuous and a binary measure of deficits in motor skills, suggesting the robustness of our results. Fifth, in our resilient trajectory model adjusted for several covariates, the recruitment center (1.48 [1.00–2.19]) distinguished between Resilient and Consistently low groups. This result may indicate possible measurement biases according to the centers and the period of evolution. Finally, our groups of participants were not based on specific DSM DCD diagnoses, but it seems highly plausible that most children with DCD characterized by deficits in motor skills at 5–6 years are part of the Consistently low and Declining groups.

Conclusion

This study provides a better understanding of children's natural history of developmental coordination delays by identifying the influence of cognitive factors that predict changes in motor skills between the ages of 3 and 5–6 years. Based on our results, the assessment of language delays and symptoms of inattention in children with deficits in motor skills is important.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical standards statement The study was approved by the Ethical Research Committee (Comité Consultatif de Protection des Personnes dans la Recherche Biomédicale) of Bicêtre Hospital and by the Data Protection Authority (*Commission Nationale de l'Informatique et des Libertés*). Informed written consent was obtained from parents for themselves at the time of enrollment and for the newborn after delivery.

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