BMC Pediatrics

RESEARCH

Open Access

Investigating the link between temperamental and motor development: a longitudinal study of infants aged 6–42 months

Atsuko Nakagawa[1*], Taishi Miyachi[2], Makiko Tomida[1], Taro Matsuki[3,8], Satoshi Sumi[4], Masayuki Imaeda[5], Akio Nakai[6], Takeshi Ebara[7,8] and Michihiro Kamijima[8]

Abstract

Background Since the 1920s, motor development has been a strong research theme, focusing on infants' acquisition of motor skills, such as turning over and crawling. In the 1980s, a dynamic systems approach began emphasizing children's own motivation, which helped explain individual differences in the emergence of motor skills. However, few studies have examined factors contributing to individual differences in early motor development. In response, we investigated directional associations between temperament and motor development in children aged 6 months to 3 years.

Method The Japan Environment and Children's Study (JECS-A) recruited mothers between January 2011 and March 2014. 2,639 mothers were sent a questionnaire at 6 months, and responses were received from 1,657 of them, with full data for children aged 6 months, 2 years, and 3 years, including from three mothers of twins, were analyzed through structural equation modeling. Question items regarding fine and gross motor activities at each age were selected by pediatric neurologists specializing in developmental disorders. The Japanese version of the Little Developmental Coordination Disorder Questionnaire was administered at 42 months. Temperament was assessed through the parent-reported Behavior Questionnaire (short version) for infants, toddlers, and children. In all three measures, Surgency and Negative Affectivity were extracted, and Effortful Control, a major form of self-regulation, was found from toddlerhood onward, as in previous studies.

Results A path diagram reveals that at 6 months, Surgency and Orienting/Regulation interacted positively with the motor function (respectively, $r = .57$; $r = 40$, ps < .001). Up to about 3 years, Effortful Control plays a role in facilitating the motor function, resulting in positive effects on Control During Movement (CDM), General Coordination (GC), and Fine Motor Movement (FMM) (β = 14; β = 30; β = 37, ps < .001). Surgency had a positive effect on CDM and GC (β = 18; β = 06, ps < .001), whereas Negative Affect had a negative influence on FMM and GC (β = -.08; β = -.08, ps < .001).

Conclusion While Surgency may be a key reactive factor in early motor development, Effortful Control and Movement develop in an interactive manner.

*Correspondence:
Atsuko Nakagawa
nakagawa@hum.nagoya-cu.ac.jp
Full list of author information is available at the end of the article

Trial registration UMIN000030786.
Scientific Title: The Japan Environment and Children's Study.
Date of disclosure of the study: 2018/01/15.
Only questionnaires were administered in the study.
Keywords Coordinated movement, Temperament, Infant, Toddler, Longitudinal study

Background

From the fetal stage, the brain develops its structure and functions through interaction with the environment and sensory-motor experiences [1]. If "movement" is understood to be central to development [2], any motor deficits should affect the brain's perceptual, cognitive, and motivational functions [3, 4]. Thus the "motor" perspective is essential to exploring developmental stumbling blocks.

Studies dating back to the 1920s have described motor development as a series of universal milestones in infancy, including sitting, crawling, and walking [5, 6]. In the early 1980s, however, Esther Thelen demonstrated through treadmill stepping and other examples that the nervous system is only one component contributing to infant motor patterns [7, 8]. Within the framework of dynamic systems theory, she described how motor skills develop and are regulated. Dynamic systems theory focuses on children's own motivation in motor development and may help explain individual differences in the emergence of motor skills. In addition, Thelen also theorized about effective and appropriate early developmental interventions for each individual [4]. While research on individual differences in motor skill learning dates back more than 100 years, our understanding of how individual differences in aptitude affect motor development and its acquisition and control remains relatively poor [2, 9]. In recent years, though the relationship between individual differences in motor and executive functions has been actively investigated, little is known about children younger than 5 years of age [10,11, see 12 for a review].

The Executive Function (EF) consists of the capacity for goal-oriented regulation of one's own thoughts, actions, and emotions and plays a significant role in early learning and transition to formal schooling. EF skills depend on neural networks, including the prefrontal cortex (PFC) and anterior cingulate cortex (ACC) [13, 14]. These networks are extensively interconnected with structures in the limbic system and brainstem [15], and these interrelationships between the PFC and ACC and other areas of the brain help establish EF as a control system that both influences and is influenced by cognitive, emotional, and behavioral functioning.

As neural substrates for EF have been proposed in early development [16, 17], these individual differences have been investigated and labeled Effortful Control within a temperamental framework [18], defined as the efficiency of executive attention. The idea that attention may be the first step toward demonstrating EF skills has been advocated [19, 20]. Referring to Baddeley's model of working memory [21], the executive attention network in major attention theory is described as having an important association with EF [22]. The anterior cingulate cortex, the lateral ventral PFC and the basal ganglia have been found to involve the Executive attention network [23], which substantially overlaps with regions related to working memory [24–26].

Temperament is defined as a set of relatively consistent, biologically-based individual differences in reactivity and self-regulation [27]. Reactivity refers to an individual's initial physiological and behavioral reactions to sensory stimuli of different qualities and intensities. These reactive tendencies, namely Surgency/Extraversion (i.e., positive emotionality) and Negative Affect are largely present at birth but become increasingly stable during childhood. In addition to reactivity, a behavioral system that enables voluntary control of attention and emotion is labeled Effortful Control, defined as the ability to inhibit a dominant response in order to perform a subdominant one. Though infants are highly limited in the temperamental factor of voluntary behavioral control (e.g., the ability to effortfully inhibit behavior upon command), this skill improves considerably in the third year of life, and such improvements continue into childhood [28, 29].

Motor control has been infrequently examined in temperament research from a developmental perspective e.g., [30–32]. However, the research trends described above have led to increased interest in identifying antecedents of EF in infant skills development. As the development of the regulatory function has been studied from early infancy within the framework of temperament, there is great merit in examining its relationship with motor development. That is, the orienting attention network exerts a great deal of control over other brain networks during infancy and early childhood in terms of temperamental regulation [33]. In addition, regarding reactivity, activity or perceptual sensitivity is known to affect the rate of motor development [34]. Previous studies have documented motor activity as a subcategory of behavior in order to describe temperament rather than as a primary outcome [35]. However, since studies show that change in one developmental domain influences changes in other domains [1, 36–38], we should reconsider the link between temperamental and motor development longitudinally.

A recent key issue in motor development is Developmental Coordination Disorder (DCD), which impairs the development of coordinated muscle functions associated with various motor activities such as dexterity, posture retention, and force coordination, and is reported to have a prevalence of 5 to 8% among school-age children [39]. Such children are at risk of lower self-esteem due to their poor ability to perform tasks [40, 41], which may lead to various maladjustments in school life and in friendships [42–44] and may cause them to become withdrawn [45, 46]. Additionally, DCD may convey early signs of developmental disorders, including autistic spectrum disorder (ASD), attention deficit hyperactivity disorder (ADHD), even high rates of comorbidity [47, 48]. Despite growing recognition of the clinical importance of DCD, the pathogenesis of DCD is still unknown, nor is anything known about its neurological basis, exacerbating factors, or protective factors [39]. Accordingly, early intervention in the motor development of children with DCD is desirable, and the importance of motivating target children is widely recognized [for a review, see 49].

Motor development is usually divided into "gross" and "fine" motor development. Gross motor development involves major movements of the whole body, primarily the trunk and legs, and culminates in independent walking, climbing, and running during toddlerhood. In contrast, fine motor development focuses on the use of the shoulders, arms, and hands, and is refined into small hand and arm movements such as grasping in late infancy and throwing in toddlers and preschoolers. It primarily relies on attentional rather than motor skill, and Effortful Control abilities may make a contribution to achievement [50]. Early motor delays in crawling or walking are often danger signals of the presence of other disruptions and may affect the development of skills in other domains. Yet only one longitudinal study has directly examined motivation in relation to motor development [30]. In that study, the developmental trajectory of motor motivation in infancy was investigated longitudinally by observing infants every 3 weeks from 7 to 12 months to describe the nature of motivation to move during locomotor transitions [35]. Results showed that motivation to move continued to increase as motor milestones were reached, and infants perceived to have stronger motivation to move showed earlier achievement of four milestones: independent sitting, pulling to stand, hands-and-knees crawling, and cruising.

With motivation defined as "the energization (instigation, activation) and direction (focus, aim) of behavior" [51], temperament-related dimensions of Surgency/Extraversion and Negative Affect are directly related to motivation [52]. That is, Positive Affect is linked to motivation in young children, including selection, engagement, and sustained interest in specific activities. In contrast, Negative Affect such as fearful inhibition may lead young children to avoid or withdraw from exciting or potentially punishing situations while providing them with the time necessary to solve a problem, meet a challenge, and plan the next step [53]. In both cases, Effortful Control constitutes a foundation for competent action as well as the ability to act—or withhold action—now in the interest of future achievements. While this may not constitute motivation, it offers a flexible means of achieving a motivationally appropriate end.

In response, as part of a national birth cohort under the Japan Environment and Children's Study (JECS-A) and using items that are relatively easy for caregivers to respond to, we created a latent variable for the motor function at each age and examine its relationship with the three factors making up temperament: Surgency, Negative Affect, and Effortful Control. Since health check-ups for 3-year-old children are widespread in Japan and the results of this study could be used as part of such check-ups, we targeted children up to 3 years of age. Our hypotheses for early childhood were: 1) Temperament and motor functions development mutually influence each other at subsequent time points; and 2) From the beginning, the gross motor system may be strongly influenced by Surgency through motivation while the fine motor system may be tightly bound to the development of Effortful Control through the building of executive attention.

Method

Recruitment and procedure

The present study is an Adjunct Study of the Japan Environment and Children's Study (JECS-A). The study protocol was approved by the Ethics Committee of the Nagoya City University Graduate School of Medical Sciences (Approval No. 60–00-0574). Participants were registered with the Aichi regional sub-cohort of JECS-A. A community-based recruitment strategy was adopted at 32 obstetric hospitals and clinics providing care for pregnant women in Ichinomiya and Nagoya. Women in the early stages of pregnancy who visited an obstetrics facility were invited to participate in JECS if they met the following criteria: (1) residence within the study area; (2) estimated delivery date after August 2011; and

(3) the ability to read and write Japanese to complete the self-administered questionnaire. Of the 8,134 pregnant women deemed eligible during the recruitment period (January 2011–March 2014), 5,721 (70.3%) participants were enrolled as the baseline cohort of pregnant women [54].

Figure 1 depicts a flowchart of the inclusion process followed in this study. Of 5,721 caregivers initially contacted in 2011–2014, 3,426 agreed to participate. The adjunct questionnaire targeted 2,642 infants, for whom parents provided written informed consent. While three participants later withdrew consent, 2,639 received a questionnaire at 6 months, of which 2,448 were returned. 141 children with congenital diseases or disorders related to motor development (i.e., Apgar score < 7 1 min or 5 min after birth) or having been delivered preterm were excluded. Subsequently, 415 dropped out of the 24-month survey, and another 235 dropped out of the 42-month survey. Ultimately, responses from 1,657 caregivers, including three mothers of twins, were analyzed. Mothers in this dataset answered questionnaires specially constructed for this Adjunct Study from the onset of pregnancy until their child was 42 months old (full data). Participants' characteristics were derived from the main JECS-A dataset. Participants were rewarded with a stored-value card for each participation. Starting in August 2013, self-administered questionnaires were sent out and completed by mothers. Responses were mailed and collected until April 2019.

Motor functions

Questionnaires about sensory motor functions were administered at 6, 24, and 42 months. Question items, including fine and gross motor activities at each age, were selected through discussions with pediatric neurologists specializing in developmental disorders while referring to previous research [55, 56] (see Supplementary Material 1).

At 6 months, regarding the frequency of their infant's rolling over, caregivers were asked to choose from "never" to "frequently." Caregivers also chose one from

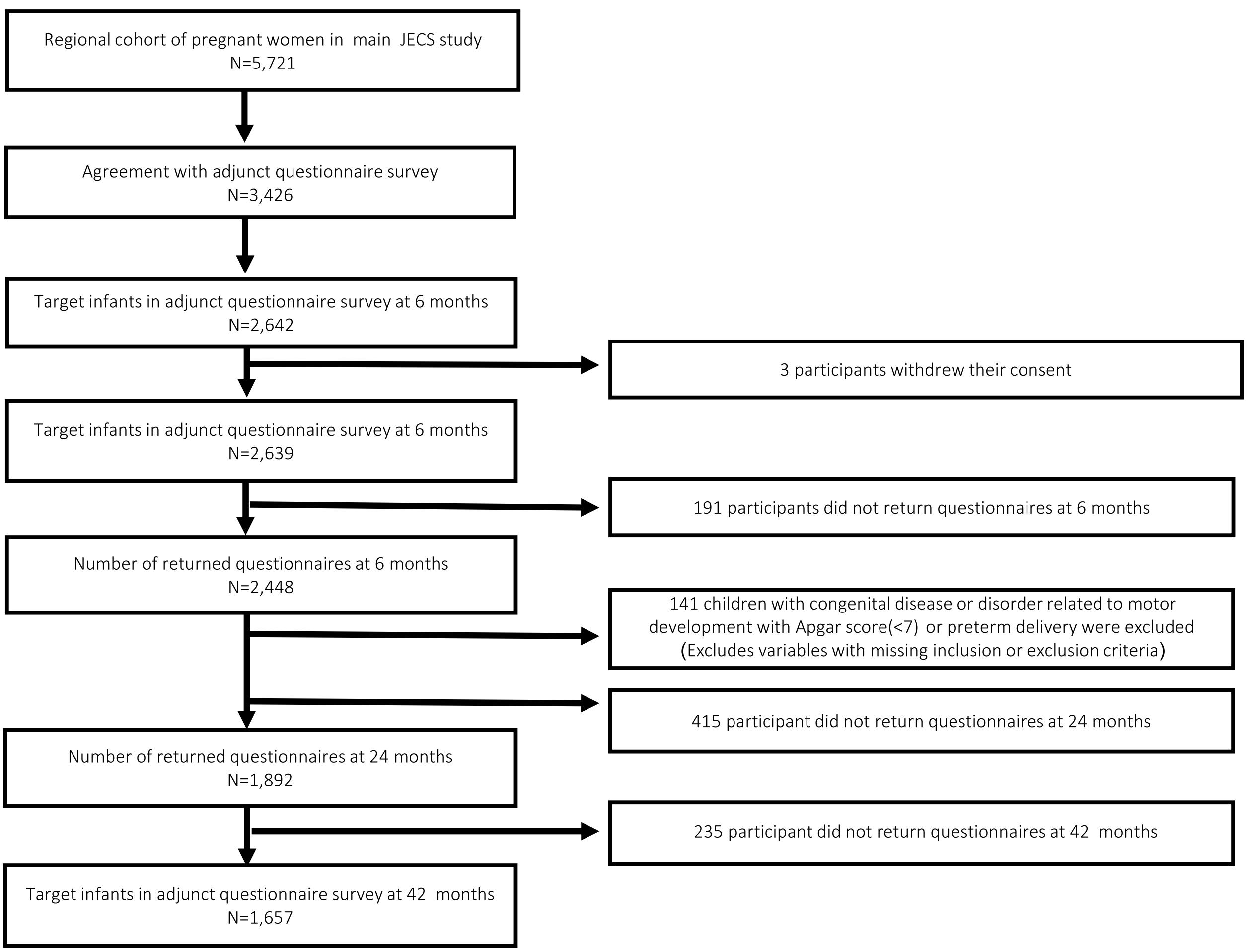

Fig. 1 Participant flow diagram

five pictures displaying the manner of rolling over. Optical righting reflexes were also assessed, with three choices offered along with illustrations. Caregivers were asked what happened to the baby's head when the baby was held upright and tilted right or left. Reaching (Does your baby try to reach objects in front of him or her?), Posture when held (Do you sense the posture of your baby as tension in the body when he or she is being held?), and Suckling (Does your baby suckle well?) were assessed, with five choices per question; reaching frequency (1; Frequently — 5; Never); degree of tenseness (1; Very tense — 5; Unstable); and Suckling proficiency (1; Very well — 5; Not well at all).

At 24 months, questions probed the onset of independent stable sitting and walking. Skills in using cutlery and picking were assessed by caregivers being presented with a list of manners of doing the above. Caregivers were asked to circle the most applicable description of their child's behavior. Regarding picking, the list was accompanied by pictures (e.g., pinching thin objects such as coins). Regarding oral dexterity, caregivers were shown six descriptions of a child eating (e.g., "My child has a strong tendency to swallow food without chewing") and asked to circle all applicable options. As three out of six descriptions were related to a motor function problem, the number of circles was counted.

At 42 months, two-leg hopping and one-leg standing were assessed by caregivers being given a list of seven manners of doing the above and asked to circle the most applicable description of their child's manner. Concerning fine motor movements, caregivers were given an illustration of a V-sign and asked to circle the most applicable from four options to describe their child's behavior (e.g., She can make the V-sign for a brief moment, but her fingers untangle quickly). The skill of using cutlery was examined by asking caregivers whether their child used a spoon to put food in his or her mouth without spilling and shown a list of manners of doing so. If they circled the "My child can use a spoon" option, they were asked to choose one from four pictures displaying the manner of doing so.

The Japanese version of the Little Developmental Coordination Disorder Questionnaire (LDCDQ) [57] was administered at 42 months. This questionnaire was developed to screen for motor coordination difficulties in 3- and 4-year olds. The 15 items are divided into 3 subcategories: Control during movement, Fine motor, and General coordination, with five items each. The first category (Control during movement) contains items relating to motor control while either the child or an object is in motion such as striking a moving ball. For each item, caregivers are asked to compare their child's performance with that of children of the same age and gender and to rate it on a five-point scale (1 = not at all relevant to my child — 5 = extremely relevant to my child), with Option 6 = never experienced added in our study. Three subcategory scores were calculated by adding ratings for all relevant items, with participants choosing Option 6 for any relevant item excluded. Higher scores indicate higher motor proficiency.

Temperament

In the present study of 6-, 24-, and 42-month-olds, temperament was assessed through the modified Japanese version of the parent-reported Infant Behavior Questionnaire-Revised (IBQ-R) [58], the Japanese short version of the Early Childhood Behavior Questionnaire (ECBQ) [59], and the Japanese short version of the Childhood Behavior Questionnaire (CBQ) [60]. In these questionnaires, to minimize parental biases associated with poor recall, aggregating information across situations prior to answering, or making comparative judgments, caregivers are given specified toddler or child reactions in concrete situations, such as "When being dressed or undressed during the last week, how often did the baby squirm or try to roll away?." Then they were asked to rate the frequency of their child engaging in the given behaviors in on a seven-point scale (1 = never — 7 = always) over the past week for the IBQ-R and the past two weeks for part of the IBQ-R (two weeks for less frequent events during the first year) and the ECBQ. In the CBQ, caregivers were given statements such as "My child always seems in a hurry to get from one place to another" and asked to rate their child on a seven-point scale (1 = totally untrue of your child — 7 totally true of your child). Caregivers were also offered a "Not applicable" response option when the child had not been observed in the situation described.

Factor analyses of subscale scores on these questionnaires yielded three broad factors of temperament. As distinct from the two broad factors of Positive Emotionality/Surgency and Negative Affect, a third factor, Orienting/Effortful Control, were extracted for the Japanese short forms of the ECBQ and CBQ [59, 60]. Regarding the temperament questionnaire at 6 months, a modified shortened version of the IBQ-R was needed to match the number of questions allocated in consideration of the burden on JECS research collaborators. Referring to Putnam and Rothbart [61], we first excluded items if more than 20% of caregivers chose the Not Applicable option for the item. Next, for each subscale, we calculated item-total correlations for the dataset [58], which included 284 infants (129 girls) with an average age of 6.79 months (SD = 2.60, range = 3 to 12). The four items with the highest item-total correlations were then used to form tentative scales. Given our aim of a minimum alpha of 0.65 for data from each subscale, the scores from the tentative scales were found to have $\alpha < 0.65$ for Cuddliness, Vocal reactivity, Low intensity pleasure, Smiling and laughter, Approach, Distress limitation, Fear, and Sadness. By adding a single item to each of these four tentative scales, we could raise internal consistency to acceptable levels for Vocal reactivity, Low intensity pleasure, Approach, and Distress limitation. Increasing two scales to six items improved internal consistency for Smiling and laughter and Fear. Based on the item-level principal axis factoring on each subscale of the standard form, items from the tentative scale were replaced by items not included in the tentative scale to ensure that all aspects of the multidimensional scale were represented. This procedure is what made us decide to retain the four-item scale, with alpha values of 0.60 and 0.61 for "Cuddliness" and "Sadness," respectively. In IBQ-R, shortening the scales had the most adverse effect on Cuddliness and Sadness, with a reliability under 0.70 [62]. Sadness was also reported to have poor consistency in the CBQ short form [61]. Due to the limitation in the number of questions in the 6-month-old JECS-A survey form, the tentative shortened version of the IBQ-R was used in the present study.

Statistical analysis

Based on a previous study [63], we hypothesized a model in which we drew assumed paths between temperament and motor function variables. Statistical analyses were conducted using IBM SPSS Statistics 25.0 (SPSS Inc.). The compatibility of data with normal distribution was tested using the Kolmogorov–Smirnov test. To confirm normal distribution, Pearson's correlation coefficient or Spearman's correlation were used to determine associations between variables. Structural equation modeling was conducted using AMOS 25.0 (SPSS Inc.) to evaluate the possible relationship between motor development and child temperament. In our model, motor function and temperament (Surgency, Negative Affect, Effortful Control) at 6, 24, and 42 months interact at subsequent time points. Moreover, these sequential relationships influence LDCDQ scores for Control during movement, Fine motor activity, and General coordination at 42 months. To develop the model, we added correlations between "error" for the three observed temperament variables each at 24 and 42 months of age and for the three observed LDCDQ variables at 42 months. Furthermore, at 24 and 42 months, correlations between "error" of the latent motor function and "error" of the three observed temperament variables were also added, respectively. Model validity was evaluated using the goodness of fit index (GFI) and adjusted goodness of fit index (AGFI) as well as the following indices to assess model fit: the chi-square statistic (χ^2), the comparative fit index (CFI), and root mean square error of approximation (RMSEA). Missing data were handled by applying a Full Information Maximum Likelihood (FIML) estimation drawing on all available data to estimate model parameters without imputing missing values. The Akaike information criterion (AIC) was also used.

Results

Tables 1 and 2 summarize the characteristics of mothers and infants, with an attrition analysis also presented. Responders ($n = 1{,}657$) and non-responders ($n = 650$) were compared based on the following data from JECA registration: Child's sex, Mother's highest level of education, Partner's highest level of education, Maternal age, Annual household income, Self-reported maternal smoking habit in the second or third trimester of pregnancy (non-smoker, ex-smoker, current smoker), and Existence of child siblings at around one month postpartum. Chi-square tests were conducted and showed that responders' partners were more highly educated, and responders smoked less often during pregnancy. However, effect size was small (Cramer's $V \leq 0.10$).

Table 2 shows reported infant characteristics and information on the temperamental and motor function variables at 6 months. Non-responders scored significantly higher than responders for Surgency, Negative Affect, and score of Rolling over though effect size (Cohen's *d*) was small (0.20 for Surgency, 0.07 for Negative Affect and 0.06 for Rolling over). Though not large, the difference in infants between responders and non-responders was significant. Table 3 presents the characteristics variables at 24 and 42 months. After testing for normal distribution, Pearson's correlation coefficient or Spearman's correlation were applied to determine associations between variables (See Table 4).

Based on a previous study [63], we hypothesized a model in which we drew assumed paths between temperament and motor function variables. Figure 2 shows the final model, in which paths found to be statistically significant ($p < 0.05$) are presented. Fit statistics indicate that the model fits the data well: $\chi^2 (264) = 1013.463$, $p < 0.001$, CFI = 0.901; GFI = 0.953; AGFI = 0.937; RMSEA = 0.041. We defined three LDCDQ scores as outcomes at 42 months. Manifest variables corresponding to the latent motor function variable loaded significantly ($p < 0.01$) for all three ages. For Stable sitting, Walking, and Oral dexterity at 24 months, lower values mean better performance, and these showed negative associations. At 42 months, the motor function showed positive associations in three categories: Control during movement ($\beta = 0.47$, $p < 0.001$), Fine motor movement ($\beta = 0.35$, $p < 0.001$), and General coordination ($\beta = 0.28$, $p < 0.001$).

With regard to temperament, all paths in line with development for Surgency, Negative Affect, and Orienting/

Table 1 Comparison of general characteristics of responders and non-responders

Characteristics	Responders (n = 1,657)		Non-responders (n = 650)		p	ES
	n	%	n	%		
Child sex						
– Female	829	(50.0)	314	(48.3)	0.46	0.02
– Male	828	(50.0)	336	(51.7)		
– Missing	0					
Mother's highest level of education						
– High school or lower	490	(29.6)	209	(32.2)	0.38	0.03
– Junior or vocational college	623	(37.6)	228	(35.1)		
– University or higher	532	(32.1)	203	(31.2)		
– Missing	12		10			
Partner's highest level of education						
– High school or lower	513	(31.0)	237	(36.5)	0.03	0.06
– Junior or vocational college	275	(16.6)	98	(15.1)		
– University or higher	844	(50.9)	303	(46.6)		
− Missing	25		12			
Maternal age						
– < 20	12	(0.7)	10	(1.5)	0.13	0.05
– 20-29	553	(33.4)	235	(36.2)		
– 30-39	1006	(60.7)	377	(58.0)		
– ≥ 40	86	(5.2)	28	(4.3)		
– Missing	0		0			
Annual household income (JPY 10,000)						
– < 200	35	(2.1)	14	(2.2)	0.84	0.03
– 200-400	423	(25.5)	167	(25.7)		
– 400-600	575	(34.7)	210	(32.3)		
– 600-800	303	(18.3)	123	(18.9)		
– 800-1000	136	(8.2)	46	(7.1)		
– ≥ 1000	79	(4.8)	36	(5.5)		
– Missing	106		54			
Maternal smoking habit						
– Non-smoker	1123	(67.8)	390	(60.0)	< 0.01	0.07
– Ex-smoker	484	(29.2)	231	(35.5)		
– Current smoker	29	(1.8)	16	(2.5)		
– Missing	21		13			
Existence of child siblings at around one						
– No	735	(44.4)	290	(44.6)	0.81	0.01
– Yes	920	(55.5)	355	(54.6)		
– Missing	2		5			

The data included three sets of twins

For the 2 × 2 chi-square test (Child sex and Existence of child siblings at around one month postpartum), we calculated φ as the effect size. For all other cases, we calculated Crammer's V.

JPY Japanese Yen, *ES* Effect size

Table 2 Comparison of reported infant characteristics of responders and non-responders

Variables	Responders (n = 1,657)		Non-responders (n = 650)		*p*	ES
	Mean	(*SD*)	*Mean*	(*SD*)		
Birth weight (g)	3082.39	(373.92)	3105.64	(385.23)	0.24	0.03
Missing	2		0			
Gestational (weeks)	39.49	(1.12)	39.54	(1.17)	0.30	0.02
Missing	0		0			
6m Temperament						
Surgency	4.55	(0.76)	4.70	(0.76)	< 0.01	0.20
Missing	0		0			
Negative Affect	3.63	(0.81)	3.75	(0.83)	< 0.01	0.07
Missing	0		0			
Orienting/Regulation	4.96	(0.71)	4.97	(0.70)	0.76	0.01
Missing	0		0			
6m Motor Function						
Rolling over	1.27	(0.80)	1.38	(0.73)	< 0.01	0.06
Missing	41		21			
Posture when held	1.83	(0.48)	1.80	(0.51)	0.12	0.03
Missing	9		5			
Optical righting reflex	2.02	(1.21)	2.05	(1.22)	0.63	0.01
Missing	51		41			
Reaching	4.78	(0.58)	4.82	(0.52)	0.49	0.04
Missing	7		2			
Sucking	3.84	(0.44)	3.87	(0.39)	0.19	0.03
Missing	1		0			

If the Kolmogorov Smirnov test revealed that the variable data was normal, we used independent *t*-tests; if not, we used Mann-Whitney-U tests. In the case of *t*-tests, we calculated Cohens' d as the effect size (ES); in the case of Utests, we calculated *r* as ES

Effortful Control were significant. Orienting/Regulation at 6 months was positively associated with Surgency at 24 months (β = 0.07, $p < 0.01$), while Negative Affect at 6 months was negatively associated with Effortful Control at 24 months (β = -0.07, $p < 0.01$). Subsequently, Surgency and Negative Affect at 24 months showed positive paths toward Effortful Control at 42 months (respectively, β = 0.10, $p < 0.001$; β = 0.10, $p < 0.001$). On the other hand, Effortful Control at 24 months was negatively associated with Surgency and Negative Affect at 42 months (respectively, β = -0.24, $p < 0.001$; β = -0.12, $p < 0.001$). Concerning the relationship between temperament and the motor

Table 3 Characteristics of variables at 24 months

	n	*Mean*	(*SD*)
24m Temperament			
Surgency	1655	4.81	(0.60)
Negative Affect	1655	3.29	(0.57)
Effortful Control	1655	4.53	(0.59)
24m Motor Function			
Walking	1644	12.73	(2.05)
Stable Sitting	1616	7.78	(1.75)
Oral Dexterity	1646	.40	(0.62)
Skill using Cutlery	1647	3.09	(0.65)
Skill Picking	1604	3.71	(0.75)
42m Temperament			
Surgency	1656	4.28	(0.72)
Negative Affect	1655	3.92	(0.61)
Effortful Control	1655	4.81	(0.61)
42m Motor Function			
One-leg Standing	1618	2.56	(0.60)
Two-leg Hop	1643	2.84	(0.41)
Skill using Cutlery	1587	2.57	(0.57)
V-Sign	1650	2.87	(0.46)
42m LDCDQ			
Control during Movement	1579	20.11	(3.49)
Fine Motor Movement	1342[a]	21.92	(3.12)
General Coordination	1605	21.45	(3.07)

[a] Fine Motor Movement Item 9 asked: "Think about other children the same age and sex as your child. Compared to them, is your child able to thread large beads onto a string?" This item returned the lowest number of participants because not many infants had such experience, which made it difficult for mothers to rate this item

LDCDQ Little Developmental Coordination Disorder Questionnaire

function, at 6 months, Surgency and Orienting/Regulation were positively correlated with the motor function (respectively, $r=0.57$, $p<0.001$; $r=0.40$, $p<0.001$). Moreover, the motor function at 6 and 24 months was positively associated with Effortful control at 24 months ($\beta=0.13$, $p<0.01$) and 42 months ($\beta=0.11$, $p<0.01$), respectively. That is, good motor function leads to good Effectful control from infancy onward. Moreover, the motor function at 24 months was also positively associated with Surgency at 42 months ($\beta=0.28$, $p<0.001$). On the other hand, there was a negative path from Orienting/Regulation at 6 months to the motor function at 24 months ($\beta=-0.09$, $p<0.05$) and a positive path from Effortful Control at 24 months to the motor function at 42 months ($\beta=0.23$, $p<0.001$). Then, as the outcome at 42 months, Surgency was positively associated with two subcategory scores for motor coordination

Table 4 Results of correlation analysis of variables used in Structural Equation Modeling

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
6m Temperament	1	6m surgency																									
	2	6m negative	.29 **																								
	3	6m orienting/ regulation	.48 **	-.14 **																							
6m Motor Function	4	6m rolling over	.12 **	.01	.01																						
	5	6m posture when held	.08 **	.00	.07 **	.00																					
	6	6m optical righting reflex	.18 **	-.01	.13 **	-.01	.14 **																				
	7	6m reaching	.29 **	.04	.21 **	.15 **	.07 **	.13 **																			
	8	6m sucking	.15 **	-.04	.14 **	-.01	.08 **	.08 **	.12 **																		
24m Temperament	9	24m surgency	.29 **	.13 **	.19 **	.02	.06 *	.07 **	.11 **	.08 **																	
	10	24m negative	.14 **	.32 **	-.05 *	-.06 *	-.06 *	.00	-.01	-.08 **	.14 **																
	11	24m effortful	.20 **	-.11 **	.35 **	.01	.09 **	.11 **	.08 **	.11 **	-.02	-.14 **															
24m Motor Function	12	24m walking	-.14 **	-.04	-.01	-.19 **	-.11 **	-.09 **	-.17 **	-.04	-.21 **	.07 **	.02														
	13	24m stable sitting	-.08 **	-.01	-.08 **	-.08 **	-.05 *	-.09 **	-.15 **	-.04	-.09 **	.09 **	-.06 *	.32 **													
	14	24m oral dexterity	-.01	.10 **	-.09 **	.01	-.06 *	-.10 **	-.04	-.09 **	.08 **	.11 **	-.17 **	.02	.01												
	15	24m skill using cutlery	.08 **	-.01	.05 *	.03	.05	.06 *	.03	.06 *	.05	-.03	.19 **	-.07 **	-.05 *	-.08 **											
	16	24m skill picking	.06 *	-.03	.10 **	.03	.09 **	.05	.07 **	.07 **	.04	-.11 **	.13 **	-.06 *	-.07 **	-.06 *	.03										
42m Temperament	17	42m surgency	.15 **	-.02	.06 *	.05 *	.04	.01	.05 *	.04	.38 **	-.12 **	-.21 **	-.21 **	-.10 **	.08 **	-.01	.02									
	18	42m negative	.06 *	.29 **	-.14 **	-.01	-.06 *	-.06 *	-.01	-.05 *	.11 **	.50 **	-.19 **	.05	.05	.11 **	-.04	-.04	-.01								
	19	42m effortful	.25 **	-.02	.31 **	.02	.06 *	.12 **	.13 **	.12 **	.15 **	.04	.50 **	-.04	-.06 *	-.10 **	.16 **	.08 **	-.14 **	-.08 **							
42m Motor Function	20	42m one-leg standing	.09 **	.00	.08 **	.03	.04	.05 *	.08 **	.06 *	.07 **	-.03	.13 **	-.20 **	-.14 **	-.05 *	.10 **	.06 *	.02	-.08 **	.19 **						
	21	42m two-leg hop	.07 **	-.03	.07 **	.05 *	.02	.06 *	.13 **	.03	.10 **	-.08 **	.12 **	-.16 **	-.14 **	-.08 **	.10 **	.14 **	.05 *	-.06 *	.13 **	.33 **					
	22	42m skill using cutlery	.06 *	-.03	.12 **	-.02	.03	.04	-.02	.03	.01	.01	.16 **	-.01	-.03	-.07 **	.13 **	.04	-.08 **	-.02	.21 **	.12 **	.11 **				
	23	42m V-sign	.00	-.01	.04	.01	.02	.02	.01	.05 *	.07 **	-.04	.11 **	-.05	-.09 **	-.04	.13 **	.08 **	-.04	-.04	.17 **	.15 **	.16 **	.10 **			
42m LDCDQ	24	42m control during movement	.26 **	.06 *	.16 **	.03	.10 **	.07 **	.15 **	.13 **	.27 **	-.04	.20 **	-.21 **	-.14 **	-.03	.14 **	.06 *	.18 **	-.07 **	.29 **	.28 **	.26 **	.09 **	.13 **		
	25	42m fine motor movement	.18 **	-.04	.20 **	.02	.12 **	.08 *	.13 **	.13 **	.14 **	-.06 *	.29 **	-.10 *	-.11 **	-.11 **	.19 **	.08 **	-.02	-.15 **	.44 **	.22 **	.20 **	.23 **	.20 **	.56 **	
	26	42m general coordination	.22 **	-.03	.22 **	.02	.11 **	.12 **	.13 **	.16 **	.18 **	-.08 **	.34 **	-.09 **	-.09 **	-.15 **	.17 **	.07 **	.03	-.15 **	.47 **	.20 **	.18 **	.16 **	.16 **	.56 **	.71 **

For correlation coefficients between temperament (6m Temerament, 24m Temperament, and 42m Temperament), between 42m Little DCDQ, or between temperament and 42m Little DCDQ, we calculated Pearson's correlation coefficients. For correlation coefficients between motor functions or between motor function, temperament and 42m Little DCDQ, we calcualated Spearman's correlation coefficients

LDCDQ Little Developmental Coordination Disorder Questionnaire

*$p < .05$

**$p < .01$

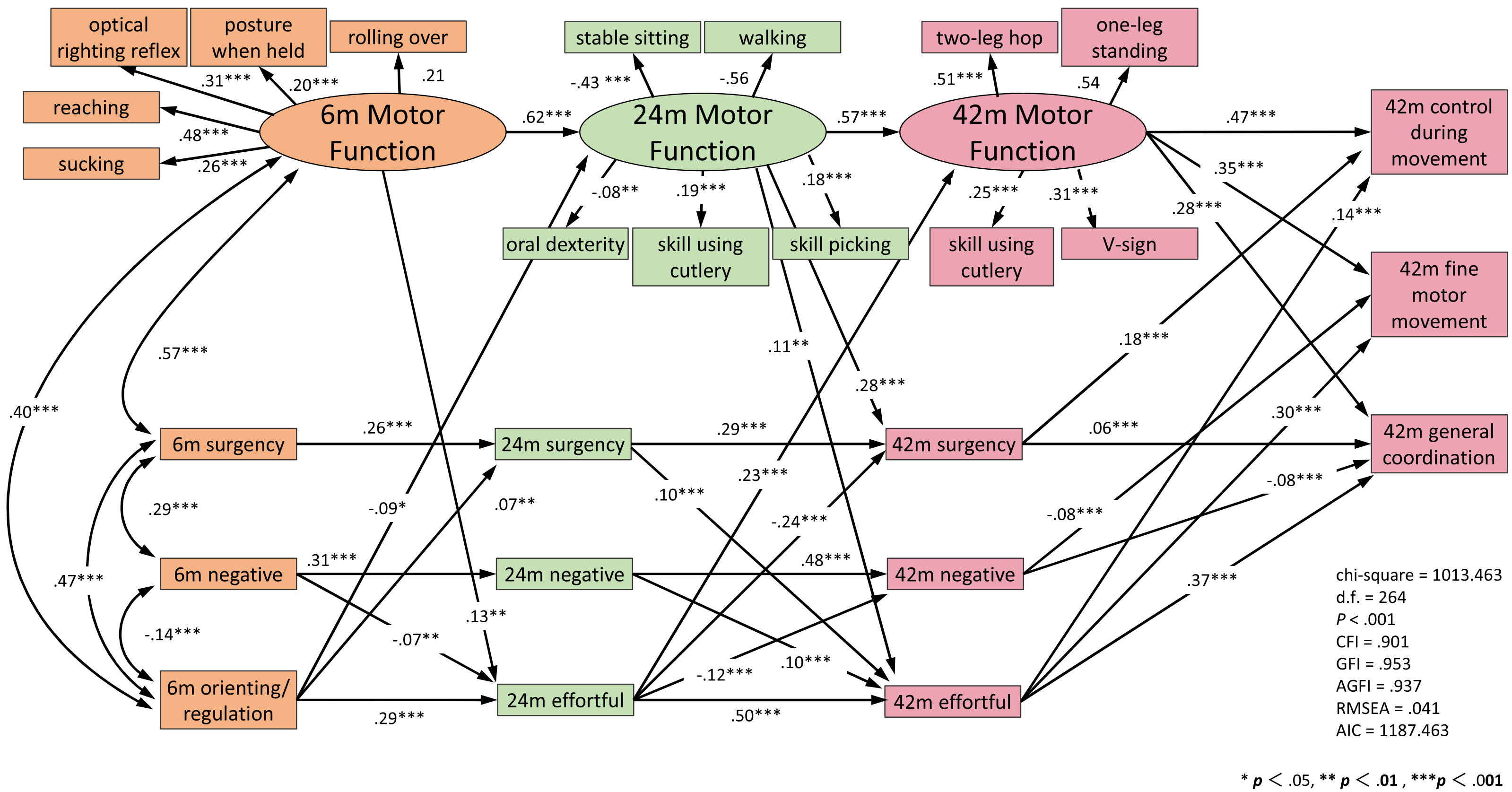

Fig. 2 Path-diagram with standardized coefficients for the structural equation model showing associations between temperamental factors and latent motor functions at 6–42 months. The error term is omitted from the figure

(Control during movement and General coordination) (respectively, $\beta = 0.18$, $p < 0.001$; $\beta = 0.06$, $p < 0.001$) except Fine motor movement, while Effortful control was positively associated with all three categories (Control during movement, Fine motor movement, and General coordination) (respectively, $\beta = 0.14$, $p < 0.001$; $\beta = 0.30$, $p < 0.001$; $\beta = 0.37$, $p < 0.001$). Conversely, Negative Affect had a negative impact on Fine motor movement ($\beta = -0.08$, $p < 0.001$) and General coordination ($\beta = -0.08$, $p < 0.001$).

The minimum sample size required for our final model was 71 based on a preliminary calculation (Alpha = 0.05, degrees of freedom in the SEM model = 267, desired power = 0.80, null root mean square error of approximation [RMSEA] = 0.05, alternative RMSEA = 0.08). We therefore judged that our sample size was satisfactory.

Discussion

The relationship between temperament and motor control was analyzed longitudinally from 6 to 42 months as part of JECS-A. As our respondents did not differ significantly in demographic data from the non-respondents who dropped out, we believe that our results can be generalized. That is, in infancy, Surgency showed a strong relationship with the motor function, while in toddlers, Effortful Control emerges to control both the motor function and temperamental reactivity in general.

High surgency in infancy can promote motor function through high activity or curiosity. Infants are fond of high intensity stimuli and highly responsive to them, eliciting encouragement from their surroundings. Later on, high motor function has positive effects on Surgency at 42 m. Surgency was also reported to be the most significant predictor of physical activity among children [64]. At 42 m, this facilitated two LDCDQ subscores, except for Fine motor movement. High surgency can be associated with roughness and clumsiness, not with improving fine motor movement.

On the other hand, Negative Affect has a negative impact on Fine motor movement and General coordination at 42 months. As these movements require motivation as well as persistence, if negative emotions are strong, children may be led to rejection or to giving up too quickly and thus not improving. Moreover, missed opportunities due to anxiety, easy anger or discomfort when things go wrong, or difficulty in being calmed may interfere with improving motor coordination. On the other hand, Control during movement is not affected by negative emotions because the questions in the subscale that ask whether or not children have difficulty with basic gross motor skills such as "running," "kicking," "throwing," or "flying." In addition, the finding that Negative Affect at 6 months has a negative impact on Effortful Control at 24 months might indicate that strong Negative affect interferes with interactions with caregivers, which are thought to promote the development of orienting attention in infancy [33].

In contrast to reactive aspects, the temperamental regulatory function may reflect a longitudinal mediation model. That is, motor development is mediated by temperamental self-regulation, and vice versa. Although the regulatory function at 6 months negatively affects the motor function at 24 months, as shown in Fig. 2, we found positive correlations between these variables (Table 4). Thus this sign reversal could be caused by strong correlation between the motor function at 6 months and 24 months [65]. In addition, Reactivity, Surgency, and Negative Affect at 24 months positively affect Effortful Control at 42 months. This may be consistent with the finding that infants with higher levels of Orienting/Regulation also show evidence of stronger levels of emotionality in a task undertaken while in distress along with evidence of efforts to self-regulate emotional reactivity [66]. On the other hand, from 24 to 42 months, Effortful Control works in the direction of suppressing reactivity, i.e., Surgency and Negative Affect. The widely-used behavior tasks assessing Effortful Control require suppressing dominant emotional or motor responses and performing subdominant behaviors [29] such as slowing down fine skills (e.g., drawing) or gross skills (e.g., walking along a 6-foot line slowly). In general, observed paths in Effortful Control for emotional reactivity and movement from 24 to 42 months were consistent with previous studies [18, 28, 33, 66].

As the LDCDQ includes items requiring attention and self-control, our results showing a positive relationship between Effortful Control and LDCDQ scores are in line with expectations. The combination of motor impairment and executive function deficits is common in children with DCD, especially those with persistent DCD over a 2-year period from Times 1 to Time 2, the 2-year follow-up [67]. As higher-order control functions develop separately from the motor function and may work as a compensatory strategy for reduced efficiency [68], careful assessments for DCD and the executive function could prove useful.

Our study has several limitations. First, we used original question items to investigate the development of the motor function in which movement is not directly observed by an evaluator with specialized knowledge. To help caregivers without such knowledge evaluate this function, we asked questions, whenever possible using illustrations along with explanations. Although multiple-choice questions are easy to answer, some actions observed by caregivers may not be available as options, or caregivers may be unable to choose between options. Further refinement of each item is needed in the future in order to make this questionnaire more effective in identifying the need for intervention at a young age. Second, temperament was also assessed through a parent-reported questionnaire. In particular, the questionnaire for 6-month-olds was tentative because the number of items was limited in light of the overall volume of the questionnaire and of the burden it placed on participants. Though the temperament questionnaire at 6 months did not show a high reliability coefficient, we accepted it because we did not wish to unnecessarily narrow the conceptual range by making it a short scale in the present study. While the results observed for temperament at 6 months were generally consistent with previous studies, we should be aware of the limitations of the tentative version of the 6-month temperament scale. As Putnam et al. argue [61], the standard version should be used for temperament studies whenever possible. Third, approximately 40% of children born in the study area have taken part in the study to date, reflecting a representative population in the regional subcohort of the JECS-A study [54]. However, in our study, a person was classified as "lost to follow-up" if any one of the three follow-up questionnaires was not returned within one year after the last one was sent out. Our attrition analysis showed that there was little difference between the maintenance and dropout groups. However, it is possible that the infants in the dropout group were slightly reactive.

As noted above, as Effortful Control has a generally positive effect on motor development, we should encourage it from the early stages. On the other hand, Surgency seems to have both positive and negative effects (positive on the gross motor system and negative on the fine motor system). Thus it will be necessary to adjust Surgency appropriately, making it neither too strong nor too weak. In addition, since Negative Affect may have increased negative effects on coordination movements at 42 months, it will be desirable to avoid giving the child excessive negative experiences by refraining from scolding or criticizing the child's behavior. On the other hand, high Effortful Control scores among preschool children have been reported to be associated with lower physical activity and greater sedentary time [69]. Understanding how the development of Effortful control relates to motor development and even adaptive functioning may lead to effective early intervention [70]. At the same time, it will be desirable to develop screening items that can be easily answered by parents with no expertise in infant motor development.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12887-024-05038-w.

Supplementary Material 1.

Acknowledgements

The authors wish to thank all the toddlers and families who took part in this project. We also thank Dr. Yasuyuki Yamada, Yuka Kimura, and Eri Kuno for their contribution to data collection. We are especially appreciative of the many individuals who assisted in data collection and coding.

Authors' contributions

A.N. and T.M. designed each adjunct study and secured funding. M.T. performed the analysis and prepared figures 1-2. T.Ma. did data curation and validation. T.M., S.S., M.I, and Ak.N. developed the questionnaires for motor development and interpreted the data. T.E. organized the study team and supervised data collection. M.K., the principal investigator for the Japan Environment and Children's Study (JECS), was responsible for study design and protocol. A.N. wrote the first draft of the manuscript. All authors reviewed the manuscript and approved the final draft and the findings.

Funding

This study was supported by JSPS Kakenhi Grants JP16H0373, 19H01655 and Grant-in-Aid for Research in Nagoya City University Grant No. 2015110. The JECS study was funded by the Ministry of the Environment, Japan. The findings and conclusions of this study are solely the responsibility of the authors and do not represent the official views of the funding agencies. The sponsors had no role in the design, execution, interpretation or writing of the study.

Availability of data and materials

Data are unsuitable for public deposition due to ethical restrictions and the Japanese legal framework. The Act on the Protection of Personal Information (Act No. 57 of 30 May 2003, amended 9 September 2015) prohibits publicly depositing data containing personal information. Ethical Guidelines for Medical and Health Research Involving Human Subjects enforced by the Japanese Ministry of Education, Culture, Sports, Science and Technology and the Ministry of Health, Labour and Welfare also restrict the open sharing of epidemiologic data. All inquiries about access to data should be addressed to: jecs-en@nies.go.jp. The person responsible for handling enquiries sent to this e-mail address is Dr Shoji F. Nakayama, JECS Programme Office, National Institute for Environmental Studies.

Declarations

Ethics approval and consent to participate

The JECS protocol was reviewed and approved by the Ministry of the Environment's Institutional Review Board on Epidemiological Studies (Ethical Number: 100910001) and the Ethics Committees of all participating institutions. The present adjunct study was approved by the Ethics Committee of the Nagoya City University Graduate School of Medical Sciences (No. 60-00-0574). The JECS was designed in accordance with the Helsinki Declaration, and written informed consent for participation in the study is obtained from individual mothers and their partners, and for infants from their parent.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

[1]Graduate School of Humanities and Social Sciences, Nagoya City University, 1 Mizuho-Ku, Nagoya, Yamanohata, Mizuho-Cho 467-8501, Japan. [2]Nagoya Western Care Center for Disabled Children, Nagoya, Japan. [3]Department of Psychology, Faculty of Health and Wellness Sciences, Hiroshima International University, Higashi-hiroshima, Japan. [4]Faculty of Nursing, Kinjo Gakuin University, Nagoya, Japan. [5]Northern Regional Children Rehabilitation Center

Yotsuba, Nagoya, Japan. [6]Research Institute for Education & Graduate School of Clinical Education, Mukogawa Women's University, Nishinomiya, Japan. [7]Department of Ergonomics, Institute of Industrial Ecological Sciences, University of Occupational and Environmental Health , Kitakyushu-Shi, Japan. [8]Department of Occupational and Environmental Health, Graduate School of Medical Sciences, Nagoya City University, Nagoya, Japan.

Received: 1 November 2023 Accepted: 28 August 2024
Published online: 28 September 2024

References

1. Adolph KE, Hoch JE. Motor development: Embodied, embedded, enculturated, and enabling. Annu Rev Psychol. 2019;70:141–64. https://doi.org/10.1146/annurev-psych-010418-102836.
2. von Hofsten C. An action perspective on motor development. Trends Cogn Sci. 2004;8(6):266–72. https://doi.org/10.1016/S1364-6613(04)00101-9.
3. Diamond A. Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. Child Dev. 2000;71(1):44–56. https://doi.org/10.1111/1467-8624.00117.
4. Thelen E. Dynamic systems theory and the complexity of change. Psychoanal Dial. 2005;15(2):255–83. https://doi.org/10.1080/10481881509348831.
5. Gesell A. Maturation and infant behavior patterns. Psychol Rev. 1929;36:307–19.
6. McGraw MB. Growth: A Study of Johnny and Jimmy. New York: Appleton-Century Crofts; 1935.
7. Thelen E, Bates E. Connectionism and dynamic systems: Are they really different? Dev Sci. 2003;6(4):378–91. https://doi.org/10.1111/1467-7687.00294.
8. Thelen E, Smith LB. Dynamic Systems Theories. Handbook of Child Psychology: Theoretical Models of Human Development (6th ed.). Edited by: Lerner, RM, Damon W. New York: Wiley; 2006, 258–312.
9. Anderson DI, Lohse KR, Lopes TCV, Williams AM. Individual differences in motor skill learning: Past, present and future. Hum Mov Sci. 2021;78:102818. https://doi.org/10.1016/j.humov.2021.102818.
10. Houwen S, van der Veer G, Visser J, Cantell M. The relationship between motor performance and parent-rated executive functioning in 3- to 5-year-old children: What is the role of confounding variables? Hum Mov Sci. 2017;53:24–36. https://doi.org/10.1016/j.humov.2016.12.009.
11. Veldman SLC, Hammersley ML, Howard SJ, Stanley RM, Okely AD, Jones RA. Associations of gross motor skills with self-regulation and executive function in preschool-aged children. Australas J Early Childhood. 2023;48(3):234–46. https://doi.org/10.1177/18369391231175524.
12. Willoughby MT, Hudson K. Contributions of motor skill development and physical activity to the ontogeny of executive function skills in early childhood. Dev Rev. 2023;70:1–20. https://doi.org/10.1016/j.dr.2023.101102.
13. Fjell AM, Walhovd KB, Brown TT, Kuperman JM, Chung Y, Hagler DJ Jr, et al. Multimodal imaging of the self-regulating developing brain. Proc Natl Acad Sci USA. 2012;109(48):19620–5. https://doi.org/10.1073/pnas.1208243109.
14. Petersen SE, Posner MI. The attention system of the human brain: 20 years after. Annu Rev Neurosci. 2012;35:73–89. https://doi.org/10.1146/annurev-neuro-062111-150525.
15. Bush G, Luu P, Posner MI. Cognitive and emotional influences in anterior cingulate cortex. Trends Cogn Sci. 2000;4(6):215–22. https://doi.org/10.1016/S1364-6613(00)01483-2.
16. Fiske A, Holmboe K. Neural substrates of early executive function development. Dev Rev. 2019;52:42–62. https://doi.org/10.1016/j.dr.2019.100866.
17. Cuevas K, Bell MA. Infant attention and early childhood executive function. Child Dev. 2014;85(2):397–404. https://doi.org/10.1111/cdev.12126.
18. Rueda MR, Posner MI, Rothbart MK. The development of executive attention: Contributions to the emergence of self-regulation. Dev Neuropsychol. 2005;28(2):573–94. https://doi.org/10.1207/s15326942dn2802_2.
19. Garon N, Bryson SE, Smith IM. Executive function in preschoolers: A review using an integrative framework. Psychol Bull. 2008;134(1):31–60. https://doi.org/10.1037/0033-2909.134.1.31.
20. Hendry A, Jones EJH, Charman T. Executive function in the first three years of life: Precursors, predictors and patterns. Dev Rev. 2016;42:1–33. https://doi.org/10.1016/j.dr.2016.06.005.
21. Baddeley A. Is working memory working? The fifteenth Bartlett Lecture. Q. J. Exp. Psychol. A: Hum Exp Psychol. 44A(1):1–31. https://doi.org/10.1080/14640749208401281
22. Rothbart MK, Posner MI. Mechanism and variation in the development of attentional networks. Handbook of Developmental Cognitive Neuroscience. Edited by: Nelson CA, Luciana M. Handbook of Developmental Cognitive Neuroscience. Edited by: Nelson CA, Luciana M. 2001, Cambridge: MIT Press; 2001:353–63.
23. Posner MI, Rothbart MK. Research on attention networks as a model for the integration of psychological science. Annu Rev Psychol. 58:1–23. https://doi.org/10.1146/annurev.psych.58.110405.085516.
24. Posner MI, DiGirolamo GJ. Executive attention: Conflict, target detection, and cognitive control. The Attentive Brain. Edited by: Parasuraman R. Cambridge: MIT Press; 1998. p. 401–23.
25. Nagy Z, Westerberg H, Klingberg T. Maturation of white matter is associated with the development of cognitive functions during childhood. Cogn. Neurosci. 16(7):1227–33. https://doi.org/10.1162/0898929041920441
26. van Ede F, Nobre AC. Turning Attention Inside Out: How Working Memory Serves Behavior. Annu Rev Psychol. 2023;74:137–65. https://doi.org/10.1146/annurev-psych-021422-041757.
27. Rothbart MK, Derryberry D. Development of individual differences in temperament. Advances in Developmental Psychology, vol. 1. Edited by: Lamb ME, Brown AL. Hillsdale: Erlbaum; 1981. p. 37–86.
28. Posner MI, Rothbart MK. Attention, self-regulation, and consciousness. Philos Trans R S Lond B Biol Sci. 1998;353(1377):1915–27. https://doi.org/10.1098/rstb.1998.0344.
29. Kochanska G, Murray KT, Harlan ET. Effortful control in early childhood: Continuity and change, antecedents, and implications for social development. Dev Psychol. 2000;36(2):220–32. https://doi.org/10.1037/0012-1649.36.2.220.
30. Boonzaaijer M, Suir I, Mollema J, Nuysink J, Volman M, Jongmans M. Factors associated with gross motor development from birth to independent walking: A systematic review of longitudinal research. Child Care Health Dev. 2021;47(4):525–61. https://doi.org/10.1111/cch.12830.
31. Missiuna C, Campbell WN. Psychological aspects of developmental coordination disorder: Can we establish causality? Curr Dev Disord Rep. 2014;1(2):125–31. https://doi.org/10.1007/s40474-014-0012-8.
32. Rahimi-Golkhandan S, Steenbergen B, Piek JP, Caeyenberghs K, Wilson PH. Revealing hot executive function in children with motor coordination problems: What's the go? Brain Cogn. 2016;106:55–64. https://doi.org/10.1016/j.bandc.2016.04.010.
33. Posner MI, Rothbart MK, Sheese BE, Voelker P. Developing Attention: Behavioral and Brain Mechanisms. Adv. Neurosci. 2014;405094. https://doi.org/10.1155/2014/405094
34. Kristal J. The Temperament Perspective: Working with Children's Behavioral Styles. New York: Brookes; 2005, p. 93–95.
35. Atun-Einy O, Berger SE, Scher A. Assessing motivation to move and its relationship to motor development in infancy. Infant Behav Dev. 2013;36(3):457–69. https://doi.org/10.1016/j.infbeh.2013.03.006.
36. Berger SE. Locomotor expertise predicts infants' perseverative errors. Dev Psychol. 2010;46(2):326–36. https://doi.org/10.1037/a0018285.
37. Campos JJ, Anderson DI, Barbu-Roth MA, Hubbard EM, Hertenstein MJ, Witherington D. Travel broadens the mind. Infancy. 2000;1(2):149–219. https://doi.org/10.1207/S15327078IN0102_1.
38. Heiman CM, Cole WG, Lee DK, Adolph KE. Object interaction and walking: Integration of old and new skills in infant development. Infancy. 2019;24(4):547–69. https://doi.org/10.1111/infa.12289.
39. American Psychiatric Association. Diagnostic and Statistical Manual of Mental Disorders. 5th ed. Washington: DC; 2022.
40. Schoemaker MM, Kalverboer AF. Social and affective problems of children who are clumsy: How early do they begin? Adapt Phys Act Q. 1994;11(2):130–40. https://doi.org/10.1123/apaq.11.2.130.
41. Piek JP, Baynam GB, Barrett NC. The relationship between fine and gross motor ability, self-perceptions, and self-worth in children and adolescents. Hum Mov Sci. 2006;25(1):65–75. https://doi.org/10.1016/j.humov.2005.10.011.

42. Lingam R, Jongmans MJ, Ellis M, Hunt LP, Golding J, Emond A. Mental health difficulties in children with developmental coordination disorder. Pediatrics. 2012;129(4):e882–91. https://doi.org/10.1542/peds.2011-1556.
43. Green D, Payne S. Understanding organizational ability and self-regulation in children with developmental coordination disorder. Curr Dev Disord Rep. 2018;5(1):34–42. https://doi.org/10.1007/s40474-018-0129-2.
44. Poulsen AA, Ziviani JM, Cuskelly M, Smith R. Boys with developmental coordination disorder: Loneliness and team sports participation. Am J Occup Ther. 2007;61(4):451–62. https://doi.org/10.5014/ajot.61.4.451.
45. Kirby A, Sugden DA. Children with developmental coordination disorders. J R Soc Med. 2007;100(4):182–6. https://doi.org/10.1177/014107680710011414.
46. Piek JP, Bradbury GS, Elsley SC, Tate L. Motor coordination and social-emotional behavior in preschool-aged children. Int J Disabil Dev Ed. 2008;55(2):143–51. https://doi.org/10.1080/10349120802033592.
47. Barnhart RC, Davenport MJ, Epps SB, Nordquist VM. Developmental coordination disorder. Phys Ther. 2003;83:722–31. https://doi.org/10.1093/ptj/83.8.722.
48. Gillberg C, Kadesjö B. Why bother about clumsiness? The implications of having developmental coordination disorder (DCD). Neural Plast. 2003;10:59–68. https://doi.org/10.1155/NP.2003.59.
49. Smits-Engelsman B, Verbecque E. Pediatric care for children with developmental coordination disorder: Can we do better? Biomed J. 2022;45(2):250–64. https://doi.org/10.1016/j.bj.2021.08.008.
50. Liew J, Chen Q, Hughes JN. Child effortful control, teacher-student relationships, and achievement in academically at-risk children: Additive and interactive effects. Early Child Res Q. 2010;25(1):51–64. https://doi.org/10.1016/j.ecresq.2009.07.005.
51. Elliot AJ, Dweck CS. Competence and motivation: Competence as the core of achievement motivation. In: Elliot AJ, Dweck CS, editors. Handbook of Competence and Motivation. Edited by: Elliot AJ, Dweck CS. New York: Guilford Publications; 2005. p. 3–12.
52. Rothbart MK, Hwang J. Temperament and the development of competence and motivation. Handbook of Competence and Motivation. Edited by: In: Elliot AJ, Dweck CS. New York: Guilford Publications; 2005. p. 167–84.
53. Rothbart MK, Ahadi SA, Hershey KL. Temperament and social behavior in childhood. Merrill-Palmer Q. 1994;40(1):21–39.
54. Ebara T, Yamada Y, Shoji N, et al. Cohort profile: Aichi regional sub-cohort of the Japan Environment and Children's Study (JECS-A). BMJ Open. 2019;9(11). https://doi.org/10.1136/bmjopen-2018-028105.
55. Teitelbaum P, Teitelbaum O, Nye J, Fryman J, Maurer RG. Movement analysis in infancy may be useful for early diagnosis of autism. Proc Natl Acad Sci. 1998;95(23):13982–7. https://doi.org/10.1073/pnas.95.23.13982.
56. Teitelbaum O, Benton T, Shah PK, Prince A, Kelly JL, Teitelbaum P. Eshkol-Wachman movement notation in diagnosis: The early detection of Asperger's syndrome. Proc Natl Acad Sci. 2004;101(32):11909–14. https://doi.org/10.1073/pnas.0403919101.
57. Nakai A, Mitsuhashi Y, Kawatani M, Wilson B, Rihtman T, Parush S. The development of the Japanese version of the Little Developmental Coordination Disorder Questionnaire (little DCDQ) (In Japanese). No To Hattatsu. 2012;186:S256.
58. Nakagawa A, Sukigara M. How are cultural differences in the interpretation of infant behavior reflected in the Japanese Revised Infant Behavior Questionnaire? Japanese J Ed Psych. 2005;53(4):491–503. https://doi.org/10.5926/jjep1953.53.4_491.
59. Nakagawa A, Kimura Y, Sukigara M, Mizuno R. The development of a short form of the Japanese Early Childhood Behavior Questionnaire (In Japanese). Stud Humanit Cultures. 2011;16:1–15 https://www.id.nii.ac.jp/1124/00000331.
60. Kusanagi E, Hoshi N. Revision of Japanese short form of the Children's Behavior Questionnaire (In Japanese). Kokugakuin Univ Hokkaido Jr Coll. 2017;34:39–53. https://doi.org/10.24626/kokuteanc.34.0_39.
61. Putnam SP, Rothbart MK. Development of short and very short forms of the Children's Behavior Questionnaire. J Pers Assess. 2006;87(1):102–12. https://doi.org/10.1207/s15327752jpa8701_09.
62. Putnam SP, Helbig AL, Gartstein MA, Rothbart MK, Leerkes E. Development and assessment of short and very short forms of the infant behavior questionnaire-revised. J Pers Assess. 2014;96(4):445–58. https://doi.org/10.1080/00223891.2013.841171.
63. Nakagawa A, Miyachi T, Matsuki T, Tomida M. Temperament and its relationship to motor development: A 6–42-month longitudinal study. Poster presented at the Society of Research in Child Development Biennial Meeting, 7-9. 2021.
64. Yates J, Tucker P, Johnson AM. Child temperament and physical activity in young children. Child Care Health Dev. 2023;49(5):898–905. https://doi.org/10.1111/cch.13098.
65. Shigemasu K, Yanai H, Mori T. Statistical data analyses learning through Qs and As: Dos and don'ts (2nd ed.) (in Japanese). Tokyo: Saiensu-sha; 2008. p. 105–7.
66. Rueda MR. Effortful control. Handbook of Temperament. Edited by: Zentner M, Shiner RL. New York: Guilford Press; 2012. p. 145–67.
67. Wilson P, Ruddock S, Rahimi-Golkhandan S, Piek J, Sugden D, Green D, et al. Cognitive and motor function in developmental coordination disorder. Dev Med Child Neurol. 2020;62(11):1317–23. https://doi.org/10.1111/dmcn.14646.
68. Koch JKL, Miguel H, Smiley-Oyen AL. Prefrontal activation during Stroop and Wisconsin card sort tasks in children with developmental coordination disorder: A NIRS study. Exp Brain Res. 2018;236(11):3053–64. https://doi.org/10.1007/s00221-018-5358-4.
69. Leppänen MH, Kaseva K, Pajulahti R, et al. Temperament, physical activity, and sedentary time in preschoolers: The DAGIS study. BMC Pediatr. 2021;21(1):129. https://doi.org/10.1186/s12887-021-02593-4.
70. Zhou Q, Chen SH, Main A. Commonalities and differences in the research on children's effortful control and executive function: A call for an integrated model of self-regulation. Child Dev Perspect. 2012;6(2):112–21. https://doi.org/10.1111/j.1750-8606.2011.00176.x.

Publisher's Note