Divergent Development in Dyspraxic Children

Part I

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Abstract

This paper reports results from a large online survey sent to the parents of children with Dyspraxia. We divide the results into five domains: Basic Medical History, Clinical Measures, Progression of Motor Symptoms, Early Signs, and Possible Risk Factors. These five domains allow us to analyze different aspects of Dyspraxia. For instance, in Basic Medical History we find that children with Dyspraxia have high rates of co-morbidity with ADHD and Sensory Processing Disorder. The Early Signs section shows us that many children experienced problems feeding when they were infants. By dividing our participants into three age groups, we were able to see how symptoms change over time. We found that motor challeremain a daily issue even into teenage years. Implications and limitations of our results are discussed.

Keywords: Dyspraxia, Developmental Coordination Disorder, DCD, neurodevelopment

Introduction

According to the National Center for Learning Disabilities' 2014 annual report, two out of three people have never heard of Dysgraphia, Dyscalculia, or Dyspraxia (Cortiella & Horowitz, 2014). The lack of public awareness of Dyspraxia, also known as Developmental Coordination Disorder (DCD), is reflected in the scientific literature: a simple Google Scholar search of "Attention Deficit Hyperactivity Disorder" (quotation marks included) will yield 409,000 results; "Dyslexia" will yield 206,000; and "Developmental Coordination Disorder" gets just 12,500 hits. Given that DCD is often diagnosed as performing below the 5th or 15th percentile on a test of motor function known as the Movement Assessment Battery for Children, 2nd Edition (MABC-2) (Ruiz, Graupera, Gutierrez, & Miyahara, 2003), Dyspraxia by definition has a prevalence comparable to the more well-known ADHD and Dyslexia (Wann, 2007).

Previously known as "Clumsy Child Syndrome" (Hulme, Biggerstaff, Moran, & McKinlay, 1982; Hoare & Larkin, 1991), Dyspraxia or DCD describes a set of clinical symptoms including fine motor and gross motor impairments, difficulties with handwriting and spelling, and challenges acquiring other basic skills such as getting dressed (Kirby, Davies, & Bryant, 2005). The *Diagnostic and Statistical Manual for Mental Disorders, Fifth Edition (DSM-5)* states that an individual with DCD displays "clumsiness…as well as slowness and inaccuracy of performance of motor skills (e.g., catching an object, using scissors or cutlery, handwriting, riding a bike, or participating in sports)" (American Psychiatric Association). In the clinical setting, the previously mentioned MABC-2 is frequently used to screen for these symptoms. The test includes a checklist and a brief motor assessment that measures balance, manual dexterity, aiming, and catching (Brown & Lalor, 2009). However, scientists warn clinicians that the measure's validity and reliability are inconsistent, and that it should not be used as the sole justification for a Dyspraxia diagnosis (Brown et al., 2009).

Recently, the *DSM-5* has also been found to have validity and reliability issues (Gordon & Cosgrove, 2013). In 2013, the National Institute of Mental Health (NIMH) withdrew funding from research based on *DSM-5* diagnoses because defining a disorder based on clusters of behavioral symptoms, rather than clusters of genetic, physiological, cognitive, and imaging data, hinders objective enquiry (Insel, 2013; Kupfer, First, & Regier, 2002). The NIMH diverted funding to their new research framework, "Research Domain Criteria"(RDoC). Rather than a

list of categories based on clusters of symptoms, RDoC is a matrix framework that analyzes psychopathology through the lens of neural circuits (Insel, 2013; Insel, Cuthbert, Garvey, Heinssen, Pine, Quinn, Sanislow, & Wang, 2010). The framework defines five main research domains, such as Cognitive Systems and Social Processes, and eight units of analysis to guide research within each domain, including Genes, Behaviors, and Physiology ("RDoC Snapshot", NIMH). RDoC lays the groundwork for a multidisciplinary understanding of mental illness (Insel et al., 2010). At the present time, RDoC-centered research about Dyspraxia is minimal or non-existent. For this reason, we must still discuss DCD in terms of its current diagnostic definition. However, in our analysis, we will go beyond reporting *DSM*-defined symptoms by probing participants' family history and medical comorbidities, searching for possible risk factors, and investigating the overlap between attention deficits and motor challenges. We strive toward a multidisciplinary understanding of neurodevelopmental disorders –an intellectual goal closely linked with our real-world motivation: understanding Dyspraxia will allow us to educate children and families living with Dyspraxia, propose targeted therapeutic interventions, and advocate for children to get access to the accommodations they need.

Children with DCD encounter a unique set of challenges that can impair their ability to perform in school. Fine motor challenges, one of the most noticeable symptoms in a school setting, have been widely studied (e.g., Rosenblum et al., 2008; Bo, Colbert, Lee, Schaffert, Oswald, & Neill, 2014; Ghanazideh et al., 2010). Rosenblum et al., for example, found that the handwriting of Dyspraxic children differs from Typically Developing children in numerous characteristics – beyond simple legibility. Children with DCD applied greater pressure to the paper, spent more time with their hands hovering over the paper, and wrote fewer letters in the first minute of writing (Rosenblum et al., 2008). Their hand movements were less spatially and temporally consistent (Bo et al., 2014), and their writing had a less orderly arrangement on the page (Rosenblum et al., 2008). Handwriting problems have been shown to hinder the quality of writing composition in children with DCD (Prunty, Barnett, Wilmut, & Plumb, 2016). A Dyspraxic child struggling to use a pen or pencil finds the cognitive process of verbal composition component more difficult.

An individual with Dyspraxia may face certain cognitive challenges in domains such as math and spatial reasoning, processing speed, and working memory (Kirby et al., 2005; Sumner,

Pratt, & Hill, 2016). Spatial reasoning is essential for effective tool use. When we perform a task like screwing in a bolt, we sometimes must choose a grip that is initially awkward so that during action implementation, we can efficiently perform the task (Comalli, Abraham, Foo, Lee, Adolph, & Keen, 2016). This is known as planning for "end-state comfort", and is an integral aspect of tool use (Comalli et al., 2016). In tasks requiring spatial precision, children with DCD do not plan as well as typically developing children for end-state comfort (Adams, Ferguson, Lust, Steenbergen, & Smits-Engelsman, 2016).

Many of these motor and cognitive deficits overlap with those associated with Attention Deficity/Hyperactivity Disorder (ADHD). According to some reports, up to 50% of children with ADHD also classify as Dyspraxic (Brossard-Racine, Shevell, Snider, Bélanger, & Majnemer, 2012; Watemberg, Waiserberg, Zuk, & Lerman-Sagie, 2007; Barkley, 2014). In a jump rope task, children with ADHD showed impaired timing perception and motor coordination, unable to adjust their jumping speed and/or execute simultaneous hand and foot movements (Chen, Liaw, Liang, Hung, Guo, & Wu, 2013). Given the symptoms we have discussed thus far, we imagine that a Dyspraxic participant would have similar trouble with this task.

Further investigation of the link between ADHD and DCD suggests that inattention, rather than hyperactivity, is more strongly associated with motor challenges (Fliers, Rommelse, Vermeulen, Buschgens, Faraone, Sergeant,…& Buitelaar, 2007; Martin, Piek, & Hay, 2006). Fliers et al. (2007) found a strong link between inattention and all domains of motor difficulty (fine motor, gross motor, coordination, and motor control), while Martin and colleagues (2006) found a specific connection between inattention and fine motor skills, as well as a weaker link between hyperactivity/impulsivity and gross motor skills.

The link between motor and attention disorders is supported by neuroimaging studies (e.g., McLeod, Langevin, Goodyear, & Dewey, 2014). McLeod et al., (2014) examined functional connectivity in children with DCD and/or ADHD and found similar patterns of reduced connectivity between the primary motor cortex (M1) and various regions throughout the brain, including the insula, amygdala, putamen, pallidum, right supramarginal gyrus, and bilateral inferior frontal gyri(IFG). The authors hypothesize that in the DCD group, abnormal connections between M1 and basal ganglia structures disrupt motor execution and control, while in the ADHD group, a lack of communication between M1, the Frontal Eye Fields (FEF), and

the left postcentral gyrus may lead to reduced visual attention and working memory. In both groups, M1 lacks strong connections to the IFG, interfering with fine motor control, inhibition, and sensorimotor integration. Task-based neuroimaging studies on DCD bolster the argument that DCD and ADHD share a common etiology. Numerous research teams have found functional anomalies in Dyspraxic participants' frontoparietal attention networks (e.g., Querne, Berquin, Vernier-Hauvette, Fall, Deltour, Meyer, & de Marco, 2008; Kashiwagi, Iwaki, Narumi, Tamai, & Suzuki, 2009; Zwicker, Missiuna, Harris, & Boyd, 2010). Zwicker et al. (2010) also found decreased activation in the cerebellar-parietal and cerebellar-prefrontal networks of children with DCD. The behavioral overlap found between ADHD and DCD may stem from their sharing a common neural substrate.

In the present study, we analyze detailed survey data in the hopes of gaining a deeper understanding of Developmental Coordination Disorder – where it comes from, how it progresses, and what impact it has on an individual's life. To paint a holistic picture of the disorder, we will provide a full account of the survey data in separate parts. In this first part, we look at Basic Medical History, DCD and ADHD clinical measures, Progression of Motor Symptoms, Early Signs, and Potential Risk Factors. In basic medical history, we gather information about diagnosis, family history of various conditions, and comorbidities. We found participants' experiences with dyspraxia diagnosis to be inconsistent due to the reliability issues of the MABC-2 and *DSM-5*. Examining these inconsistencies will help us understand how clinical interpretations of the disorder could be refined. Patterns of comorbidities should provide insight as to what dyspraxia can look like in a clinical setting, what challenges are associated with the disorder, and what illnesses in family history should be later investigated as risk factors.

The Clinical Measures section reports results from two diagnostic assessments within our questionnaire: the Vanderbilt ADHD Diagnostic Parent Rating Scale (VADPRS) and the Developmental Coordination Disorder Questionnaire 2007 (DCDQ'07). They receive their own section in this paper because their administration and scoring process has been established with normalized data (Wolraich, Lambert, Doffing, Bickman, Simmons, & Worley, 2003; Wilson, Crawford, Green, Roberts, Aylott, & Kaplan, 2009). The DCDQ and VADPRS provide us with quantifiable and clinically-accepted measures that will allow us to explore the relationship between DCD and ADHD and correlational analyses in other sections, such as Risk Factors.

The Progression of Motor Symptoms section helps us understand a typical Dyspraxic child's development over time. Since the diagnosis is symptoms-based, it is important to understand how these symptoms change over time. The DCDQ is only valid for children up to the age of 15; in this section we hope to challenge the validity of that cutoff by showing how motor symptoms do not disappear over time.

Just as important as exploring the persistence of motor challenges is investigating their early emergence. In the Early Signs section, we consider infant behaviors and motor milestones that may be correlated with later motor function. We try to identify reliable early-life signs that could be used to facilitate in earlier, more accurate diagnosis. Motor difficulties can emerge long before school age. Many children later diagnosed with neurodevelopmental disorders struggle with feeding or swallowing during infancy (Rogers & Arvedson, 2005). Oral feeding and swallowing is a multistage process that involves immense sensorimotor coordination and the generation of rhythmic muscle movements (Wood et al., 2002). Given the symptoms observed in school-age children with DCD and the high comorbidity of many neurodevelopmental disorders, we expect to find a high incidence of feeding disorders in our Dyspraxic cohort.

Finally, we analyze Possible Risk Factors. With so many comorbid challenges and an unclear etiology, it is important to investigate possible causes of Dyspraxia. In this section we will look at the influences of genetic predisposition, prenatal stress, birth trauma, and imbalance of gut biota.

Methods

Creating the questionnaire

The "Princeton University | Dyspraxia Questionnaire" was created on Qualtrics, an online survey platform, over the course of several months. The formation of the survey involved consulting with health care professionals, including a physical therapist and a neuropsychologist, to gain insight into how Dyspraxia presents in a clinical context. We wanted to create a questionnaire that was informative, detailed, ethnographic, and clinically and scientifically relevant. For this reason we included the two clinical measures for neurodevelopmental disorders

in our questionnaire: the Vanderbilt ADHD Diagnostic Parent Rating Scale (VADPRS) and the Developmental Coordination Disorder Questionnaire (DCDQ).

The DCDQ is a 15-item questionnaire with 5-point Likert scale questions (Wilson et al., 2009). The questions ask parents to compare their child's motor skills with those of other children. For example, the first item of the DCDQ asks, "Compared to other children…your child throws a ball in a controlled and accurate fashion." Total Scores range from 15 to 75, with a reported population average of 61.79 (SD=10.21) (Wilson et al., 2009). For 5- and 7-year-olds, any score below 46 classifies as "Suspect for DCD"; for 8- and 9-year-olds, a score below 55 indicates DCD; and for 10- to 15-year-olds, any score below 57 qualifies as "Suspect for DCD". Higher DCDQ scores indicate better motor function, which is why the cut off scores for indication of DCD are higher for older children. Almost all of our participants classified as "Suspect for DCD" according to the DCDQ (see Figure 2 under *Participant Demographics*). The DCDQ generates three subscores: Control During Movement, Fine Motor, and General Coordination, which have been validated through factor analysis (Wilson et al., 2009; Cairney, Missiuna, Veldhuizen, & Wilson, 2008; Tseng et al., 2010). These subscores do not include cutoffs to indicate DCD, but are informative as to the child's specific deficits.

The VADPRS screens for the 18 *DSM-5* criteria for ADHD. The second clinical measure included in the questionnaire was the VADPRS, which screens for ADHD and anxiety. Like the DCDQ'07, the VADPRS utilizes a Likert scale to assess the severity of ADHD or anxiety symptoms. The 4-point scale ranges from "Never" to "Very Often". The VADPRS screens for two subtypes of ADHD: inattentive and hyperactive. Inattentive ADHD is screened with statements like "Has difficulty sustaining attention to tasks or activities" and hyperactive ADHD with statements like "Blurts out answers before questions have been completed" (Wolraich et al., 2003). When scoring the VADPRS, There are nine questions each subsection, and one point is given for each answer of "Often" or "Very Often". Accumulating six points in a single subsection indicates someone having that subtype of ADHD. To classify as having ADHD, Combined Subtype, a person must have six or more points in each subsection.

We launched the questionnaire twice: first on December 26, 2015, and then again on January 4, 2016. Participation was by invitation only. We recruited through online support groups, Facebook, and word of mouth. Interested subjects contacted a member of the lab, and

after a brief initial screening were given a link to take the survey. The length of the questionnaire varied because there were conditional questions and participants were required to enter information about their child's siblings, but the maximum length of the questionnaire was around 750 questions. Our pilot subjects reported that the questionnaire took around 2 to 3 hours to complete, but participants did not have to complete the survey in one sitting.

Data Preprocessing

In total, we received 249 responses. Data were downloaded directly from Qualtrics into Microsoft Excel as a CSV. In Excel, some of the question headings were corrected because they did not properly transfer. Next, data from both launches were aligned and concatenated. The questionnaire from the December 26 Launch did not have a question for child's age, so age was calculated in Excel using the DATEIF function. Four respondents did not provide their child's age or date of birth. In these circumstances, we estimated age based on the child's grade in school. These participants included two presumed 9-year-old males, one presumed 7-year-old-female, and a presumed 4-year-old male.

After these minor preprocessing steps, the data was trimmed, and the 48 participants who did not fill out all questions of the DCDQ'07 were excluded. These questions were crucial for standardizing the classification of our subjects into "DCD" and "non-DCD" groups, and later for analyzing the relationship between severity of DCD symptoms and other factors. Thus, we were forced to exclude subjects who did not complete the DCDQ.

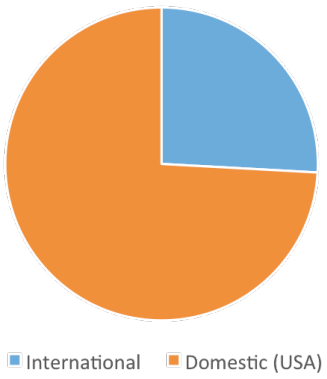
Participant Demographics

The questionnaire was directed at parents or guardians of children with DCD. After excluding incomplete responses, we found that 94% of respondents were mothers, 5% were fathers, and 1% were grandmothers of a Dyspraxic child. Depending on the number of siblings the child had, these dedicated family members answered up to 754 questions about their children.

Demographic information about our participants reveals extensive geographic diversity (Figure 1). Most of our participants were from the United States, but over a quarter came from another country. Unsurprisingly, the majority of our international participants came from Westernized, English-speaking countries such as the United Kingdom, Australia, and Canada,

but there was also a large number of individuals from other countries. A plurality of our American participants came from the Northeast, but all geographic regions were represented.

A



B

Country	# of Participants
UK	13
Australia	9
Canada	7
Italy	6
Ireland	1
Germany	1
Finland	1
Malta	1
Singapore	1

C

US Region	# of Participants
Northeast	42
Midwest	27
South	32
West	21

Figure 1. Geographic distribution of participants
(A) Most of our participants are from the United States, and about a quarter are from other countries. (B) Most international participants lived in Western, English-speaking countries such as UK, Australia, and Canada. However, there were still a notable amount of participants from other countries. (C) Geographic divisions based on the current census bureau classifications. Note that 32 of the 42 participants from the Northeast came from the "tristate area" (NJ, NY, and PA)

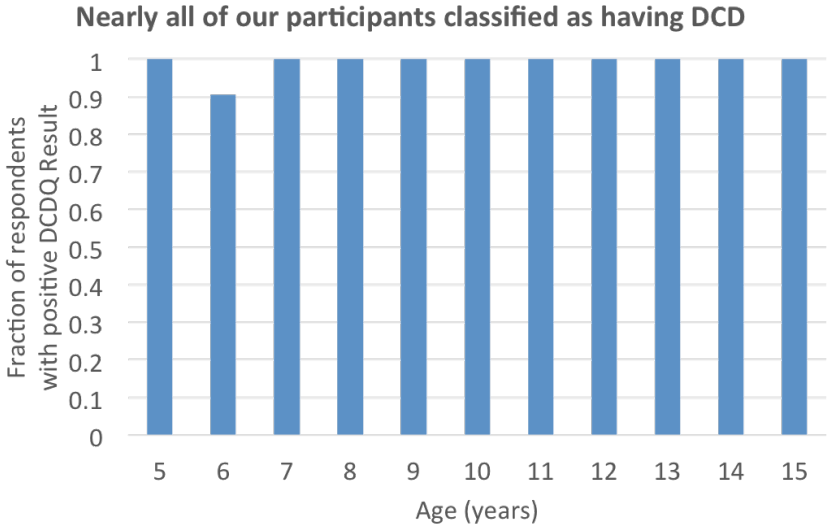


Figure 2. Nearly all of our participants classified as having DCD
We invited parents of children with DCD to participate in our study. Indeed, we found that almost all of our participants showed a clinical indication of DCD, supporting the validity of the DCDQ included in our questionnaire.

According to the results from the DCDQ (see Results, Clinical Measures) almost all of our participants show a clinical "indication of Dypsraxia" (Wilson et al., 2009; Figure 2). This is unsurprising, since we targeted dyspraxia children; however, this result is important to check the validity of the DCDQ to use for diagnosing DCD. The age distribution of participants is shown in Figure 3A. The gender ratio of DCD diagnosis is reported to be ~ 1 girl : 3 boys (McCarthy, 2015). In our sample, we had a ratio of roughly 1 : 2.2 (Figure 3B)., While the male participants (blue bars) show a roughly normal age distribution, the distribution of female participants has a slightly more pronounced positive skew. Thus, when we divide participants into three age groups in the following analyses, we have the lowest proportion of girls in the oldest age group (10 to 15-year-olds). 27% of our participants were either ambidextrous or left-handed (Figure 3C), reflecting previous findings that left-handedness is more prevalent in the Dyspraxic population (Goez & Zelnik, 2007).

Data Analysis

191 participants completed the entire DCDQ. The median score for these participants was 26. Since nearly all of our participants classified as Dyspraxic, we created two categories of severity: "Severe DCD" and "Mild DCD", to help us analyze risk factors and other measures of interest. Any participant with a score above the median was classified as "Mild DCD", while any score below the median was classified as "Severe DCD". There were 95 participants in each group, and age was comparable – the Mild DCD group had a mean age of 8y10mo and a standard deviation of 2y11mo, and the Severe DCD group had a mean age of 8y2mo and a standard deviation of 2y6mo. Analysis was performed using Microsoft Excel and MATLAB.

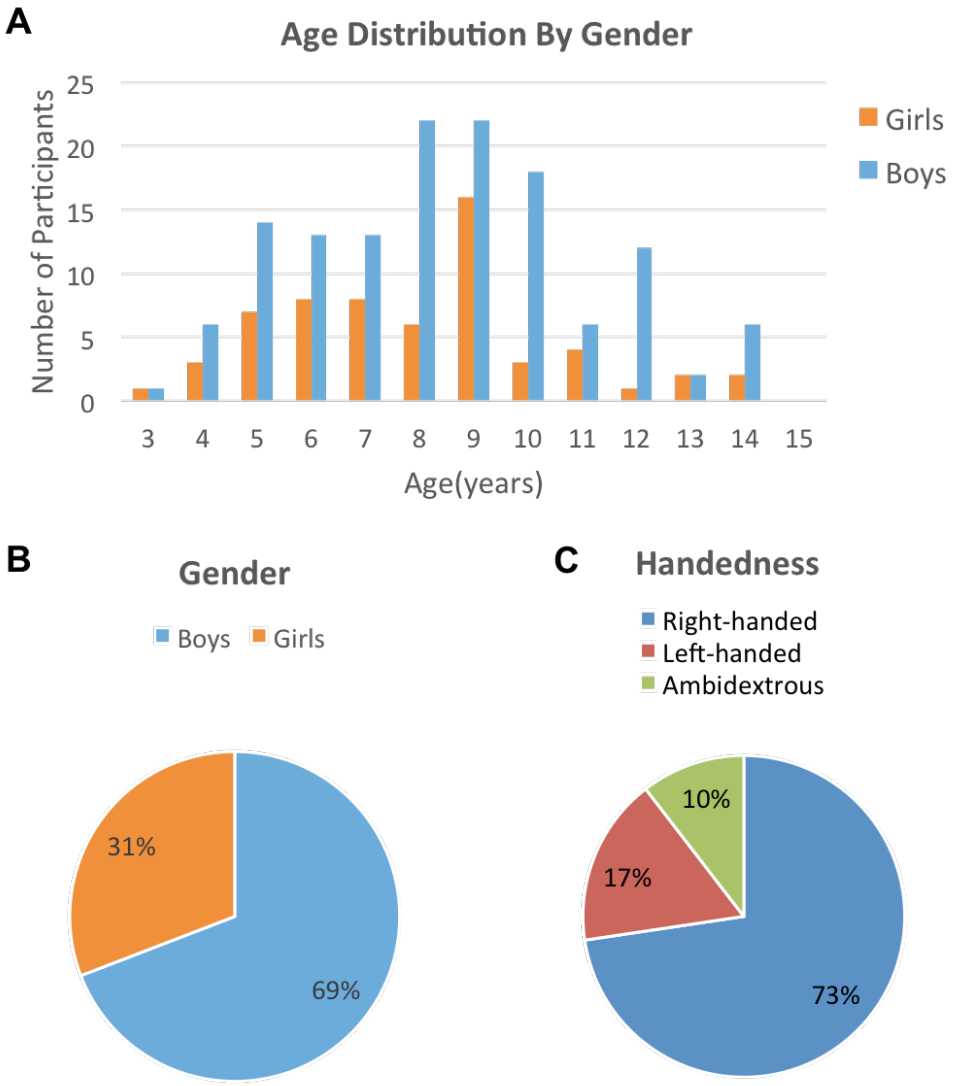


Figure 3. Demographics of cohort: age, gender, and handedness
(A) We have a roughly Gaussian age distribution, with more boys in each age group than girls, except for ages 3 and 13 years. For the subsequent analyses in the paper, we will collapse the subjects into the three age divisions used in the DCDQ: 5-7, 8-9, and 10-15. Each of these groups contains roughly 60 subjects.
(B) Around 30% of our participants were female, reflecting the commonly noted gender bias in Dyspraxia diagnosis.
(C) Estimates for the prevalence of left-handedness and ambidexterity vary, but a sizeable number of our participants reported being ambidextrous or left-handed.

Results

Basic Medical History

For basic medical history, we were interested in the prevalence of certain comorbidities among children and their immediate family members. We wanted to look into neurodevelopmental comorbidities because of reported overlaps between ADHD, DCD, ASD (e.g., Kadesjo & Gillberg, 2001; Pauc, 2005). Psychiatric disorder are of interest because having a child with Dyspraxia could add stress to family members' lives and lead to clinically significant symptoms; additionally, there may be some genetic or epigenetic correlations between certain psychiatric and neurodevelopmental disorders. Gathering information on medical comorbidities will allow us to explore the established link between inflammation, gut biota, and neurodevelopmental disorders (e.g., Hsiao, McBride, Hsien, Sharon, Hyde, McCue… & Patterson, 2013).

First, we studied parent medical history, specifically the prevalence of various neurodevelopmental (NDD), medical, and psychiatric disorders among our respondents (Figure 4). In Figure 4A, we find that ADHD, Dyslexia/other Learning Disability, and "Other" are the most common neurodevelopmental diagnoses among the parents. Most who responded "Other" were either diagnosed with a less common condition, such as sensory processing disorders, or they suspected that they or the child's other parent had an undiagnosed neurodevelopmental disorder. The prevalence of ADHD in the parent cohort is 18%, while current estimates of the prevalence of adult ADHD range from 2.9% (Faraone, Sergeant, Gillberg, & Biederman, 2003) to 4.4% (Kessler, Adler, Barkley, Biederman, Keith, Conners… & Zaslavsky, 2006). We also asked whether the parents ever had psychiatric disorders in the past or the present. As shown in Figure 4B, anxiety and depression are the most common psychiatric diagnoses in our parent cohort. According to the National Comorbidity Survey Replication, a large-scale mental health survey distributed in the United States, 26.3% of men and 21.9% of women met the criteria for clinical depression (Martin, Neighbors, & Griffith, 2013). Our cohort's prevalence, at 34%, exceeded this. The national prevalence of anxiety disorders is estimated at 3.7-4.2% (Baxter, Scott, Ferrari, Norman, Vos, & Whiteford, 2014), while 31% of the parents from our survey reported anxiety.

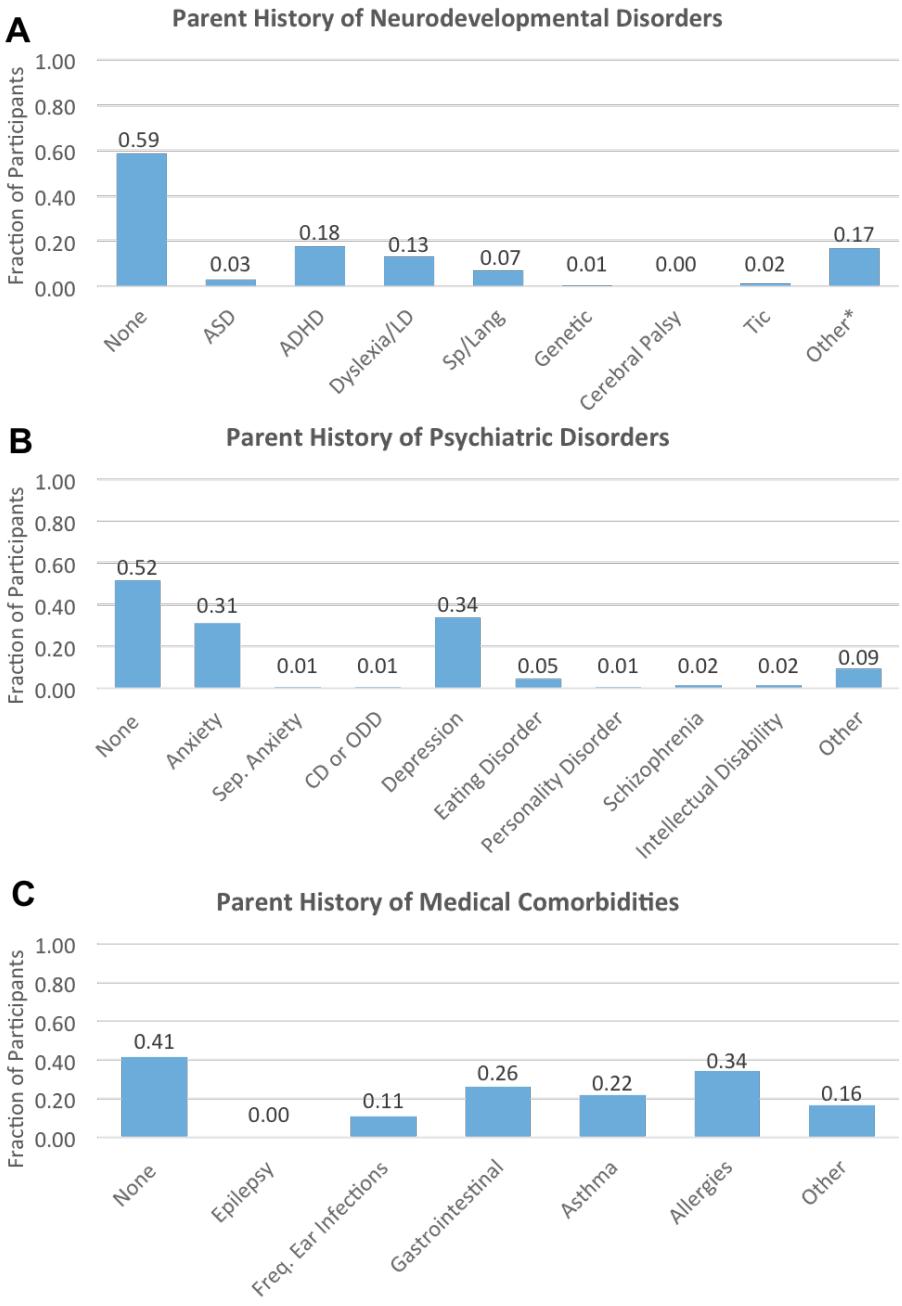


Figure 4. Prevalence of neurodevelopmental, psychiatric, and medical diagnoses among parents
(A) Most common diagnoses in neurodevelopmental disorders are ADHD and Dyslexia. *Other includes parent with diagnoses such as sensory processing disorder and those who suspect they or their spouse has DCD, ADHD, or some other undiagnosed developmental challenge.
(B) We asked whether the parents ever had psychiatric disorders in the past or present. **Other includes diagnoses such bipolar or other mood disorders, OCD, trichotillomania, and transgender dysphoria.
(C) Our parent cohort shows ~33% prevalence of allergies. ***Other includes issues such as congenital hearing impairments, Multiple Sclerosis, Ehlers-Danlos Syndrome, aplastic anemia, Barrett's esophagus, and thyroid issues.

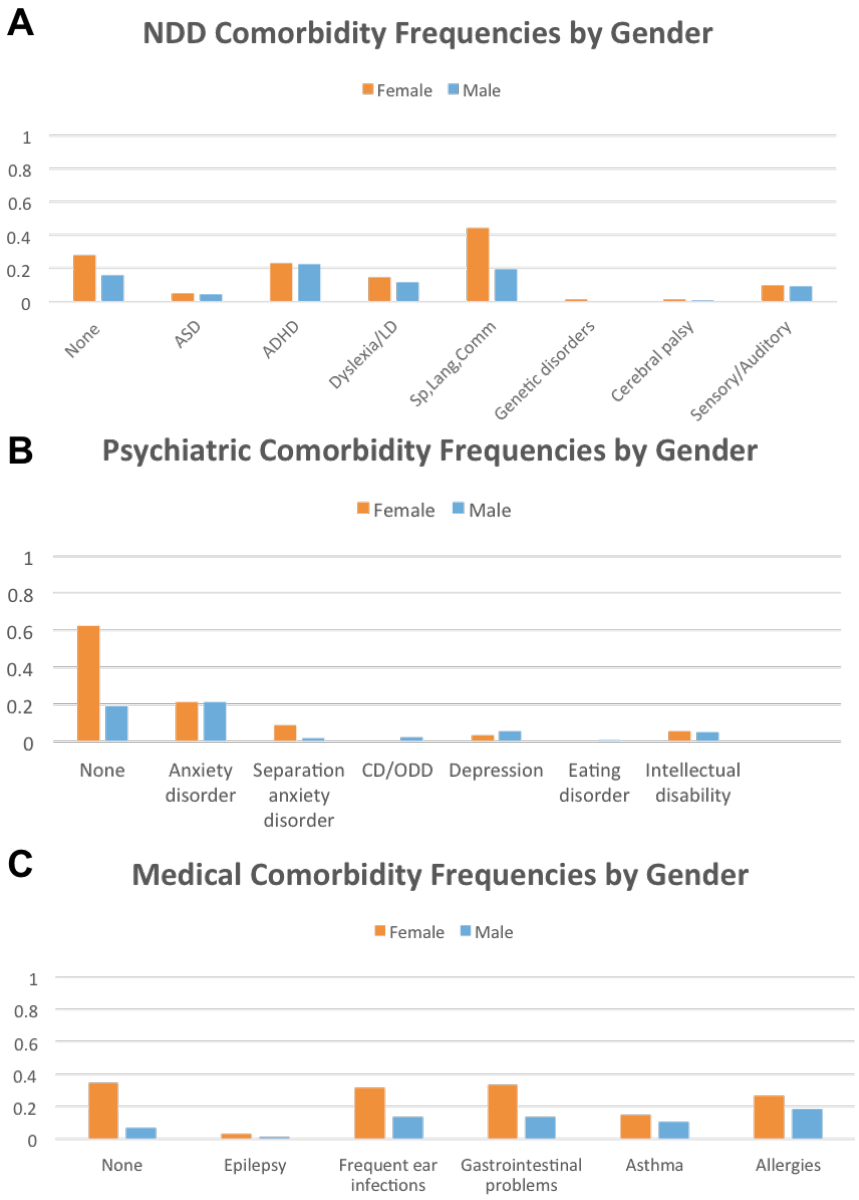


Figure 5. Prevalence of neurodevelopmental, psychiatric, and medical comorbidities among children
(A) The most common neurodevelopmental comorbidities were Speech, Language, and Communication Disorders. ADHD and Dyslexia/Learning Disorders were The last category, Sensory/Auditory Processing Disorder, was not originally an option in the multiple choice section. However, so many people wrote it in as a free-response answer that we created another category in this graph to reflect its prevalence.
(B) Note the low prevalence of depression. In the comment section, many parents expressed concern about their children showing signs of depression or anxiety, but had not gotten their children assessed; the true prevalence of both anxiety and depression is likely higher.
(C) Medical problems are more common in girls.

Figure 4C shows the prevalence of certain medical conditions among the parents. Among those included in the survey, allergies, gastrointestinal problems, and asthma were the most common. 34% of parents reported allergies; 26% reported gastrointestinal problems, and 22% reported having asthma. The prevalence of asthma in our cohort (22%) exceeds the 2010 US national prevalence of asthma, which was reported at 9.3% (Akinbami, Simon, & Rossen, 2015).

Figure 5 shows the prevalence of the same comorbidities among the children in our study, separately for boys (blue) and for girls (orange). The most common NDD comorbidity in girls was Speech, Language, and Communication Disorders, with a prevalence of 44%. Only 20% of boys reported this diagnosis. The second-most prevalent NDD in girls was ADHD (prevalence = 23%). ADHD was the most prevalent NDD in boys, with 23% of boys reporting an ADHD diagnosis. The third-most prevalent NDD for both genders was "Dyslexia or Other Learning Disorder": 15% of boys and 12% of girls reported having this comorbidity. Unlike the parent cohort (Figure 4A), sensory/auditory processing disorders were of the most frequent comorbidities in children (Figure 5A). This category of neurodevelopmental disorders was not originally included in our questionnaire, but we decided to include it as a new category because 10% of boys and girls reported having a sensory/auditory processing disorder in the "Other" section.

Figure 5B reveals that the most common psychiatric comorbidity in children is anxiety, with a prevalence of 21% in boys and girls. Separation anxiety, depression, and intellectual disability are the next-most common, with the prevalence of these disorders falling below 10% for both genders. Like the parent data for medical comorbidities, we see in Figure 5C a high prevalence of inflammation-related medical challenges, including gastrointestinal problems, frequent ear infections, and allergies. 32% of girls and 12% of boys reported frequent ear infections; 34% of girls and 12% of boys reported gastrointestinal problems; and 26% of girls and 19% of boys reported allergies.

Another aspect of medical history we wanted to learn about was the Dyspraxia diagnosis process. In the questionnaire, we asked, "Who diagnosed your child?" and "What was the official diagnosis?" Figure 6A shows the number of diagnoses made by each type of medical specialist (such as neuropsychologist or developmental pediatrician). Occupational therapists were most frequently cited as the person who gave the diagnosis (53 diagnoses out of 191).

Neuropsychologists made 44 diagnoses, and pediatricians made 39. Neurologists, developmental pediatricians, and child study teams also made a significant number of diagnoses. Note that many respondents described the diagnosis process as a complicated team effort involving many different specialists and consultants. Here we evaluated the responses on a case-by-case basis and focused on who took the lead on making the diagnosis. For example, neurologists could have contributed to more than 20 diagnoses in our cohort, but they only took the lead on 20.

Figure 6B presents different diagnoses given to our participants. 82 children were given the label "Dyspraxia" or "DCD/Developmental Coordination Disorder". Outside of these labels, however, there is immense heterogeneity. 14 children received the diagnosis of "Motor and/or speech apraxia", a broad category that encompasses a collection of similar diagnoses, including Childhood Apraxia of Speech, Developmental Articulation Disorder, Dysarthria, Verbal/Oral Dyspraxia, Motor Apraxia, and Speech Apraxia. In addition to these more common labels, there were 10 other diagnoses reported, each of which had one to three children per diagnostic category. We were also interested in comparing diagnosis statistics between girls and boys (Figure 5, Figure 6C, Table 1). As shown in Figure 6C, 88.5% of girls and 85.6% of boys in our cohort had received an official DCD diagnosis. The average age at diagnosis was 5 years and 3 months for girls and 5 years and 11 months for boys although this gender difference was not statistically significant.

Table 1. Gender disparities in number of comorbidities

	Male	Female
Medical	1.28 (1.15)	1.12 (1.13)
Psychiatric*	0.63 (.77)	0.40 (.63)
Neurodevelopmental	1.44 (1.1)	1.07 (.88)

In each diagnosis domain, boys are on average diagnosed with a greater number of comorbidities per person. There was a gender difference only in the number of psychiatric comorbidities ($p = 0.035$), but the number of medical comorbidities ($p = 0.37$) and the number of neurodevelopmental disorders ($p = 0.98$) were not significantly different between boys and girls.

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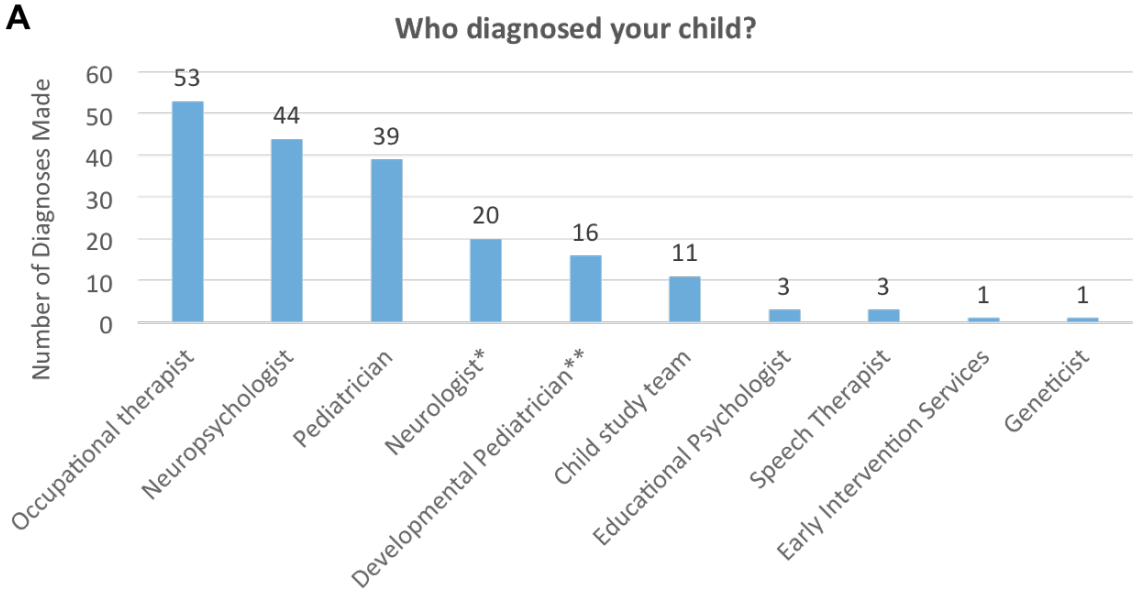


B

Diagnosis	Number of Participants with Diagnosis
DCD or Dyspraxia	82
Motor and/or speech apraxia**	14
Motor Developmental Delay	3
Sensory Processing Disorder	3
Developmental Delay	2
R27.8 Other lack of coordination	1
781.3 lack of coordination	1
Cerebellar ataxia	1
Motor clumsiness	1
F82.9 Specific developmental disorder of motor function	1
Mild Cerebral Palsy	1
Gait Apraxia	1

C

Comparing Dyspraxia Diagnosis Patterns in Girls and Boys

	Girls	Boys
Percentage with official DCD diagnosis	88.5%	85.6%
Age at Diagnosis: Average (SD)	5.29 (2.4)	5.9 (2.6)

Figure 6. DCD diagnoses

(A) Many participants described diagnosis as a "team effort" with collaboration among many different specialists. Here we show who took the lead on making the diagnosis. *Neurologist includes Pediatric Neurologist. **Developmental Pediatrician includes Neurodevelopmental Pediatrician and Developmental Behavioral Pediatrician.

(B) Diagnostic labels given to our participants. *Including "Developmental Dyspraxia", "Motor Dyspraxia, and "Global Dyspraxia" **Including Developmental Articulation Disorder, Childhood Apraxia of Speech, Dysarthria, Verbal/Oral Dyspraxia

(C) Among our sample, girls and boys show equal prevalence of Dyspraxia, and are diagnosed at roughly the same age.

Clinical Measures

The questionnaire included two established clinical measures, the Developmental Coordination Disorder Questionnaire 2007 (DCDQ'07), and the Vanderbilt ADHD Diagnostic Parent Rating Scale (VADPRS). In Figure 7, we present the average DCDQ scores and subscores for children within the three different age groups defined by the DCDQ scoring rubric: 5 to 7 years, 8 to 9 years, and 10 to 15 years (Wilson et al., 2009). In the bar graph, the x-axis represents the age group, and the y-axis represents the average DCDQ composite scores or subscores.

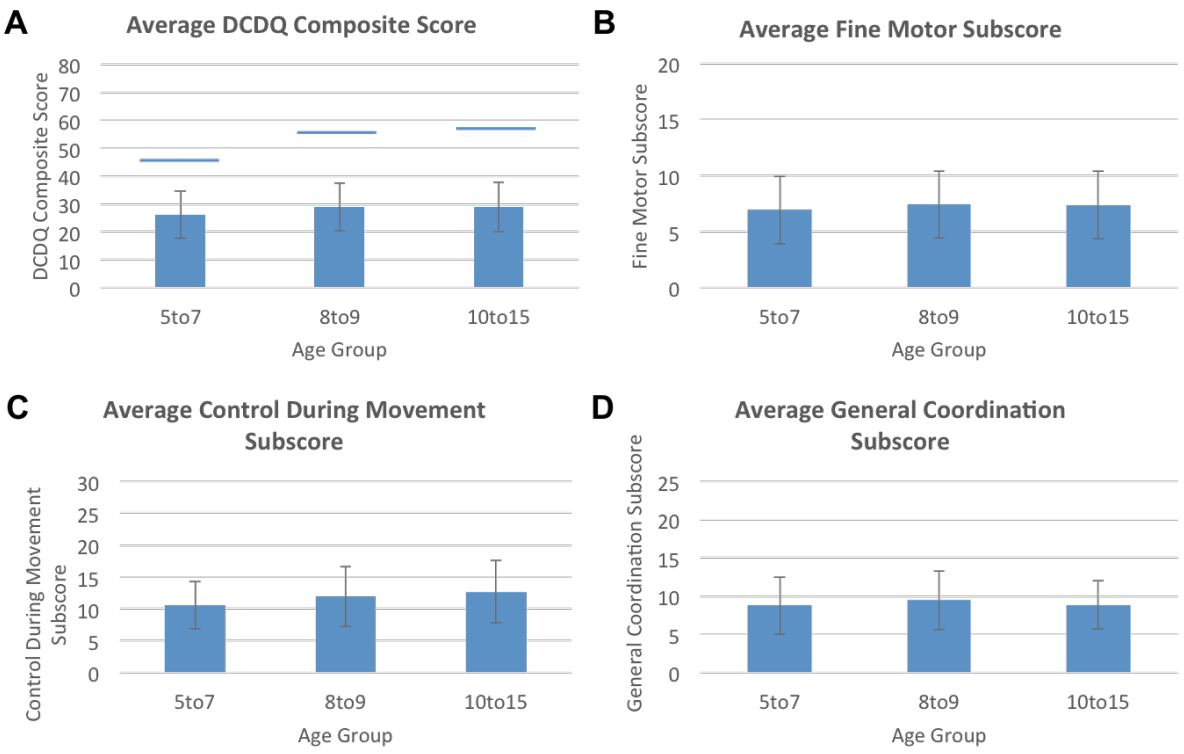


Figure 7. DCDQ average raw scores across age groups
(A) DCDQ Composite scores (error bars represent standard deviations within age group) reveals that our age groups show clinically similar motor impairments. The horizontal blue line on graph marks the DCD indication cut off for each age group: 46, 55, 57 for 5 to 7-year-olds, 8 to 9-year-olds, 10 to 15-year-olds, respectively. Scores below this cut off indicate DCD. Maximum Composite Score = 75.
(B, C, D) Average Control During Movement, Fine Motor, and General Coordination subscores for all age groups (error bars = SD within age group). No DCD indication cut-offs exist for the subscores. The maximum scores are 30, 20, and 25 for Figures B, C, and D, respectively.

The maximum score on the DCDQ is 75, and the minimum score is 15. The lower the score, the greater the motor impairment. The horizontal blue lines represent the DCD indication cut off for each age group. Scores below this line show "indication of DCD or suspect DCD" and scores above the line signify "probably not DCD" (Wilson et al., 2009). The cutoff score rises across age groups because motor function is expected to improve over time. In Figure 7A, we see that average total score for all three age groups remains relatively constant around 28. The average scores do not improve significantly even though the DCD cutoff increases, so there is a greater disparity between typically developing and Dyspraxic children's motor function in the older age groups. Figures 7B, 7C, and 7D display average subscores for the three domains covered by the DCDQ: Fine Motor, Control During Movement, and General Coordination. There is no clinical cutoff for the subscores, but the y-axis maximum for Figure 7B, 7C, and 7D represent the maximum subscores. In Figure 7B, we find that the Fine Motor subscore for all age groups is around 7 out of 20 possible points. Figure 7C shows that the average Control During Movement Score for 5 to 7 year olds is 10.6 out of 30, for 8 to 9 year olds is 12.0 out of 30, and for 10 to 15 year olds is 12.7 out of 30. This slight rise, however, is not significant. In Figure 7D, we see that average General Coordination subscores hover around 9 out of 25 for all three age groups.

Figure 8 compares average DCDQ composite scores and subscores for boys and girls across all age groups. The average composite score for both boys and girls is 28 out of 75 total possible points. There is no significant difference in average DCDQ composite scores and subscores between boys and girls. The subscore on Control During Movement averages at 12 (max = 30), Fine Motor averages at 7 (max = 20), and General Coordination averages at 9 (max = 25) for both genders.

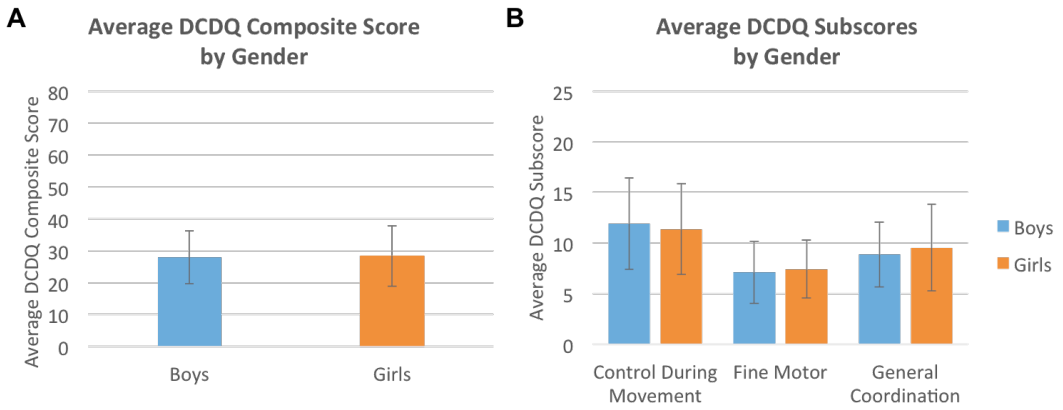


Figure 8. Average DCDQ composite score and subscores by gender
There is no significant difference in boys' and girls' average DCDQ composite scores or subscores. This analysis includes participants from all age groups. The DCD indication cut off, which changes with age group, is not included in this graph.

The Vanderbilt Attention Deficit Parent Rating Scale (VADPRS) is a clinical tool that screens for the symptoms of inattentive, hyperactive, and combined subtypes of ADHD as well as for symptoms of anxiety. Figure 9 presents the average VADPRS composite scores and subscores data for three age groups: 5 to 7 years olds, 8 to 9 year olds, and 10 to 15 year olds. Figure 9A shows the average ADHD combined scores across age groups. A person classifies as combined subtype if she scores 6 out of 9 or higher on both the Hyperactivity and Inattention subscales. Typically, a score above twelve indicates combined subtype, but a person could also attain a score of twelve due to one very high score and one lower, but not clinically significant, subscore. Therefore, there is no blue line in Figure 9A showing a clinical cut off. However, all age groups average around a combined score of 10, which is below the minimum score required to classify as Combined Subtype. Figures 9B and 9C depict average Hyperactivity and Inattention subscores, respectively. The horizontal blue lines indicate the cutoff score of six, with scores above this line indicating an ADHD subtype. All age groups on average fall below the line for Hyperactivity, ranging from 3.5 to 4.5 out of 9. 10 to 15 year olds have a lower average hyperactivity score (3.5 out of 9) than 5 to 7 year olds (4.5 out of 9), but this difference is not significant. As shown in Figure 9C, the average Inattention subscores of all three age groups are above the cutoff line, meaning that our average participant, regardless of age, classifies as having

inattentive ADHD. However, as shown in the large error bars, there is huge variability within each age group.

In addition to ADHD, the VADPRS also screens for anxiety. Scores above three (horizontal blue line in Figure 9D) indicate clinically significant anxiety. As seen in Figure 9D, only 8- to 9-year-olds have an average anxiety score above three. 5- to 7-year-olds average at 1.9 out of 7, and 10 to 15-year-olds average at 2.9 out of 7. Again the error bars for all age groups indicate that there is a large amount of variability among our participants, and that many participants may classify as having anxiety.

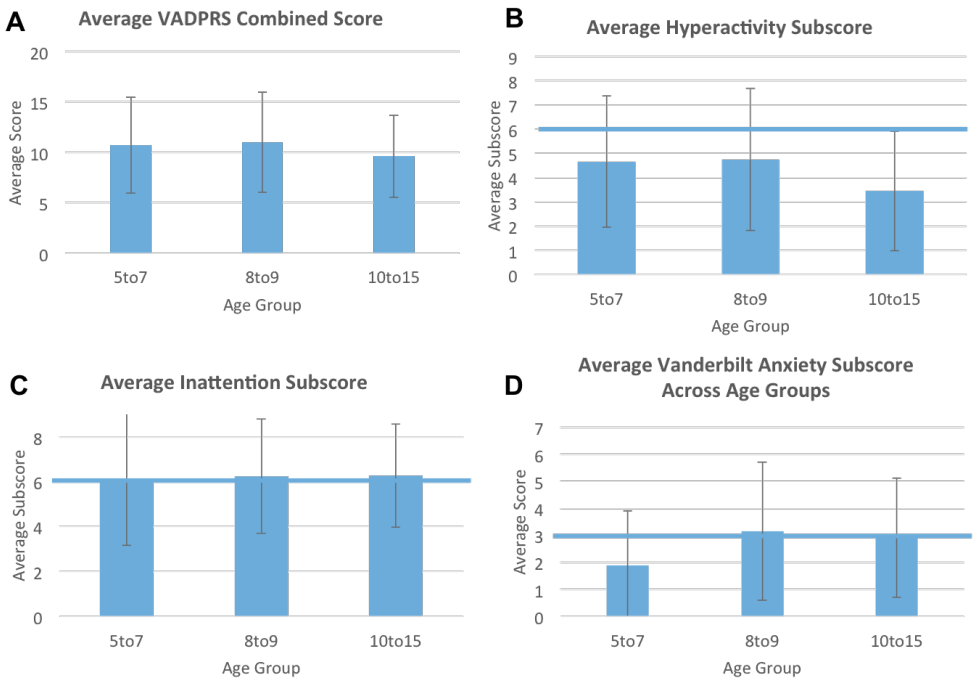


Figure 9. Average Vanderbilt ADHD Diagnostic Parent Rating Scale (VADPRS) scores across age groups
(A) Average ADHD combined score does not change significantly across age groups. The diagnosis of combined type ADHD is made when a participant's subscores for inattention and hyperactivity are above six. Thus, there is no cutoff indication marked on the graph for combined type ADHD.
(B,C) The horizontal line represents the clinical cutoff score of six; scores *above* this cutoff indicate ADHD. The average inattention subscores of all three age groups reach clinical significance. We see a slight but not significant drop in hyperactivity subscores in our oldest group.
(D) Average Anxiety subscores show a slight increase in anxiety prevalence for older age groups.

Figure 10 compares the VADPRS scores (presented in Figure 9) between boys and girls across all age groups. Boys have an average combined score of 10.5, while girls have an average combined score of 9.2 (Figure 10A). In Figure 10B, we see that boys have an average inattentive subscore of 6.3 – above the diagnostic cutoff (horizontal blue line), while girls average at 5.5. Boys also have a slightly higher average hyperactivity subscore of 4.5, compared to girls' average of 3.8. Boys also score higher on the VADPRS anxiety subscore, averaging at 2.8, whereas girls' averages at 2.4 (Figure 10C). Although there seem to be slight differences, all three differences were not statistically significant.

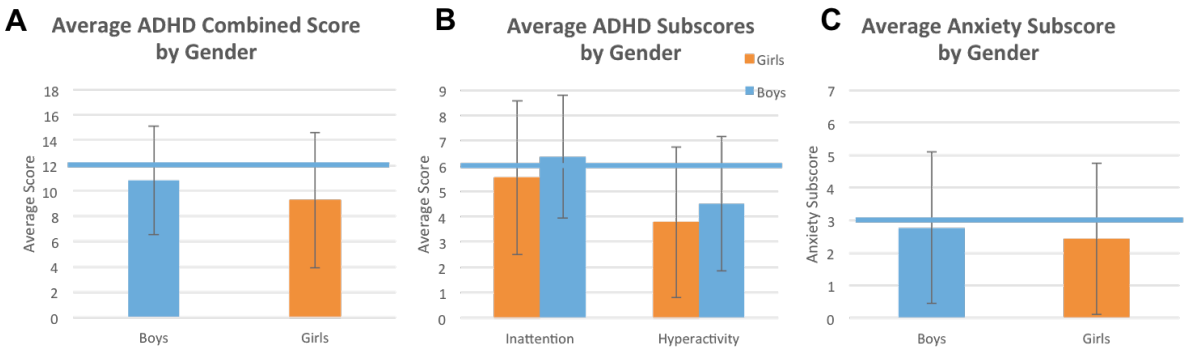
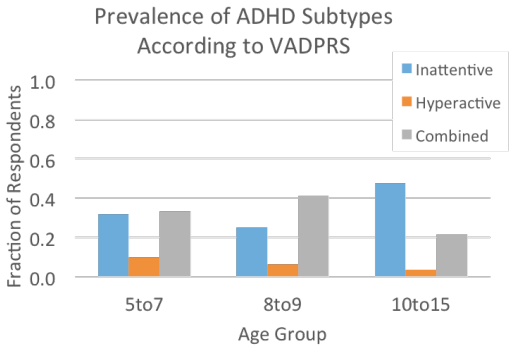


Figure 10. Average VADPRS scores (composite and subscores) for boys (blue) and girls (orange)
Horizontal blue lines in all three graphs indicate diagnostic cutoffs.
(A) Higher ADHD scores indicate higher likelihoods of ADHD. The combined ADHD score seemed to be slightly higher in boys than girls, but the difference was not statistically significant.
(B) Inattention scores are slightly higher in both genders. There was no significant gender difference.
(C) Neither gender on average reaches a clinically significant anxiety score.

The VADPRS allows us to estimate the prevalence of ADHD and Anxiety within our cohort. We find that the prevalence of Hyperactive subtype decreases over time: across the three age groups, prevalence falls from 10% to 6% to 4%, for a total prevalence of 7% for all age groups (Figure 11). Inattentive ADHD falls and then rises in prevalence: 32% of 5- to 7-year-olds, 25% of 8- to 9-year-olds, and 47% of 10- to 15-year-olds classify as Inattentive subtype, according the VADPRS. Combined type ADHD shows a pattern opposite to Inattentive ADHD: its prevalence rises, then falls. We see this in the pattern of gray bars in Figure 11A and in the data depicted in Fig 11B: 33% of 5-to7-year-olds, 41% of 8 to 9 year olds, and 21% of 10 to 15 year olds classify as having combined type ADHD. Figure 11C summarizes the bottom row of the data table in Figure 11B by showing the prevalence of the ADHD subtypes for all

participants. Inattentive and combined subtypes are the most common, while only 7% of all participants classify as having purely hyperactive ADHD.

A



B

Age Group	Inattentive	Hyperactive	Combined	No ADHD
5to7	19 (32%)	6 (10%)	19 (33%)	16 (28%)
8to9	16 (25%)	4 (6%)	26 (41%)	18 (29%)
10to15	28 (47%)	2 (4%)	12 (21%)	17 (30%)
Total	63 (34%)	12 (7%)	57 (32%)	51 (29%)

C

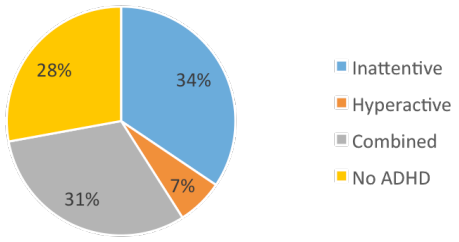


Figure 11. Prevalence of ADHD subtypes according to VADPRS
(A, B) The graph and table both show the proportion of participants within each age group indicated as ADHD subtypes (inattentive, hyperactive, and combined) based on the VADPRS scores. The prevalence of inattentive subtype is higher in the oldest participants, while combined and hyperactive subtypes are lowest in the oldest group.
(C) Roughly two-thirds of participants are inattentive or combined subtype, and very few are hyperactive.

Figure 12 reports prevalence data from the anxiety portion of the VADPRS. Anxiety prevalence does not change across age groups, and roughly 33% of participants in each age group classify as having anxiety.

Figure 13 summarizes the DCD-ADHD comorbidity patterns in our cohort. 70% of participants had both DCD and ADHD (gray), while only 28% of participants had just DCD (blue). Only three participants had ADHD only (orange) and only one participant in our entire cohort had neither ADHD nor DCD (yellow). The bar graph in Figure 13A shows that the relative prevalence of ADHD and DCD comorbidity remains relatively constant across age groups. In other words, approximately 70% of 5 to 15 year olds have ADHD and DCD, and 28% percent of participants have DCD only. However, note that all participants in the 10to15 age

group classify as either DCD only or DCD & ADHD; the few participants without a DCD diagnosis belong to the younger age cohorts.

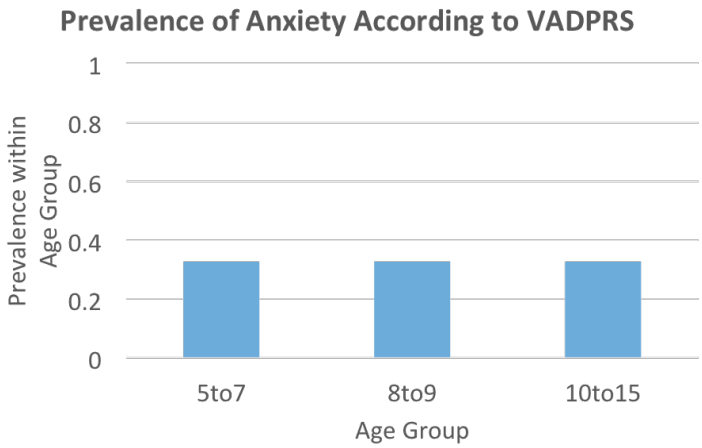
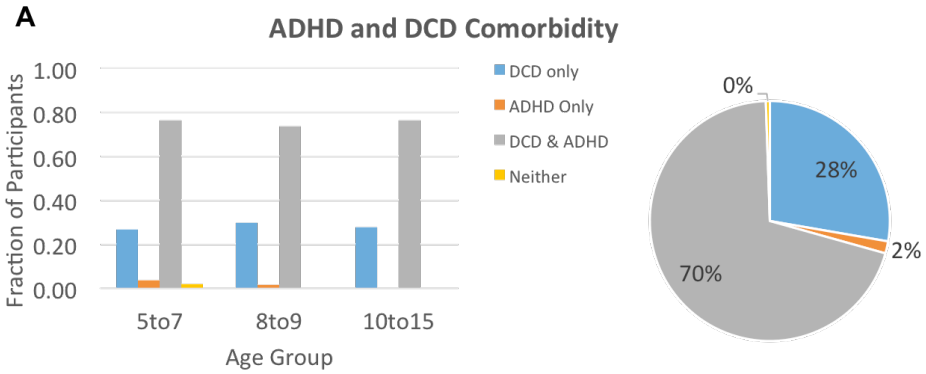


Figure 12. Prevalence of anxiety according to VADPRS



B

Age	DCD only	ADHD only	DCD & ADHD	Neither
5to7	16 (26%)	2 (3%)	42 (69%)	1 (2%)
8to9	19 (29%)	1 (1.5%)	45 (69%)	0 (0%)
10to15	16 (27%)	0 (0%)	42 (70%)	0 (0%)
Total	51 (28%)	3 (2%)	129 (70%)	1 (0%)

Figure 13. ADHD and DCD comorbidity
(A) The Bar graph shows the prevalence of DCD, ADHD, and combined DCD&ADHD for each age group. DCD&ADHD is the most common combination for all three groups. The pie chart summarizes the bottom row of the data table, showing prevalence data for all age groups combined.
(B) Prevalence data, reported as total number of participants and percentages within each age group, are presented here in table form. The percentages are equivalent to the y values in Fig. 12A. Notice how just one participant in our entire cohort has neither ADHD nor DCD.

In Figure 14, we examined the relationship between the DCDQ and VADPRS measures. There was no significant correlation between VADPRS combined scores and DCDQ composite scores (R^2 = 0.0061; Figure 14A). There was no correlation between DCDQ composite scores and VADPRS Inattention/Hyperactivity subscores (Figure 14B).

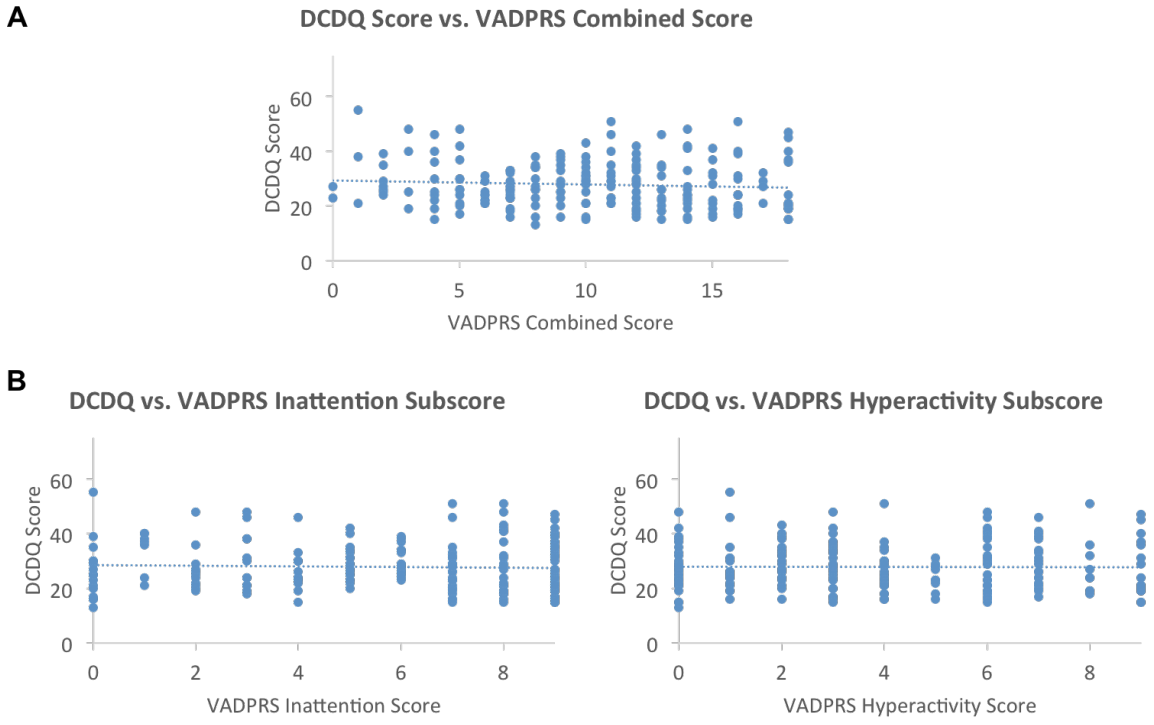


Figure 14. VADPRS-DCDQ correlation analyses
We examined correlations between DCDQ and VADPRS Scores. DCDQ scores were not correlated with either VADPRS composite scores (A) or inattention/hyperactivity subscores (B).

Progression of Motor Symptoms

Control During Movement

In our Control During Movement questions, we analyzed the time-course of motor skills such as skipping, swimming, and biking. Figure 15 shows the progression of swimming and biking ability. The bar graphs in Figures 15A and 15C depict data for four age groups: <5, 5to7, 8to9, and 10to15. The y-axis in the graph represents the proportion of participants, and the color of the bars above each age group represents one of three responses to the questions "Can your child bike?": Orange= "No", Yellow = "A little", and Green = "Yes". The green bars rise from

right to left, showing that more children in the older age groups have acquired swimming and biking skills. In Figure 15A we see that by age 10 to 15, 52% of participants can bike. According to a survey given to over 6,000 elementary school students in California, children on average learn to ride a bike at age 5.9 years (Waller, 1971). 79% of participants in the 5to7 age groups could not ride a bike. Comparing Figure 15A with 15C, we see that participants learned to swim earlier than they learned to bike; in the <5 age group, we find that no child can ride a bike and 22% can ride a little. In Figure 15C, we see that 9% of the <5 group can swim and 45% can swim a little. The pie charts in Figures 15B and 15D show that most participants struggled to learn these skills: 74% had difficulty learning to ride a bike, and 82% had difficulty learning to swim.

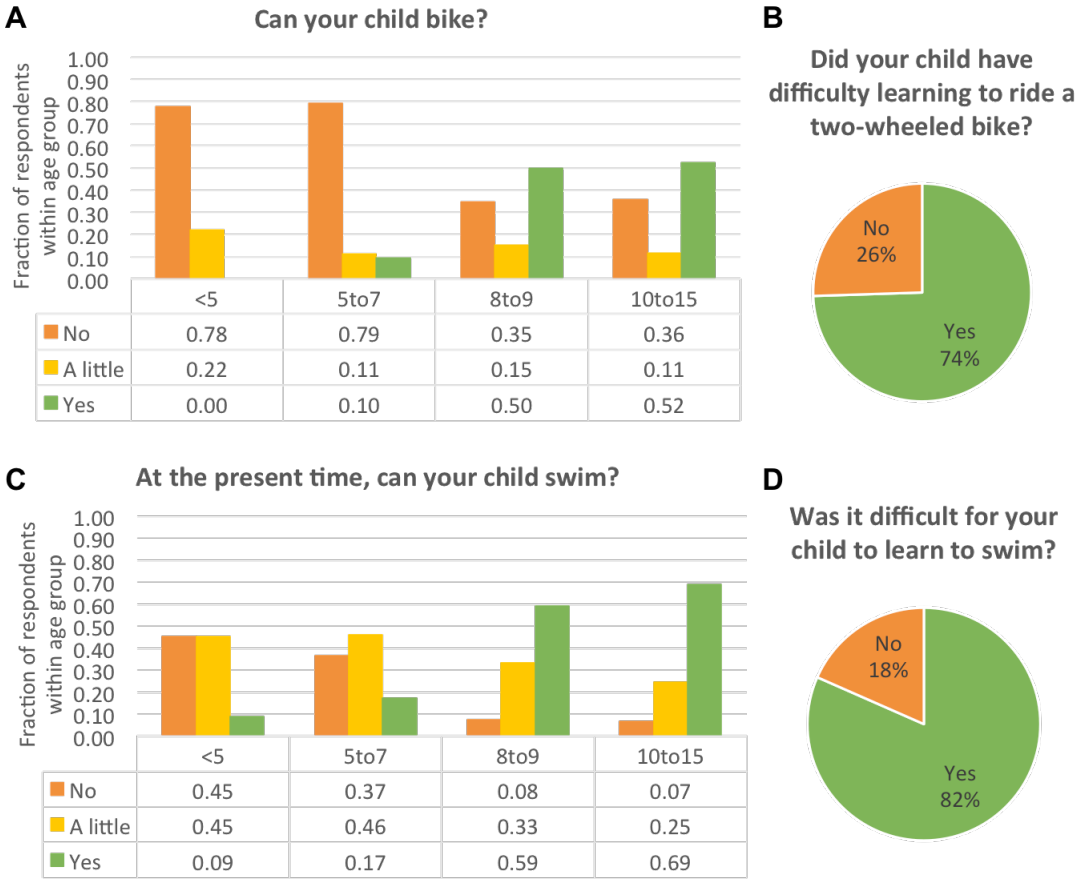


Figure 15. Control during movement delays demonstrated by biking and swimming difficulties
(A) More participants were able to bike in older age groups, indicating the progression of biking proficiency across age groups.
(B) Three-quarters of participants reported having trouble learning to ride a bike.
(C) There was a progression of swimming proficiency across the four age groups.
(D) Roughly 80% of participants reported having trouble learning to swim, compared to other children.

Figure 16 shows how children in each age group perform at various multitasking skills. Figure 16A depicts a line graphs showing the fraction of children within each age groups that can walk and talk simultaneously, can run and kick a ball, or have trouble skipping and jumping. The trends show that multitasking improves slightly over time: while 75% of 5- to 7-year-olds have trouble skipping or jumping, 55% of 10- to 15-year-olds struggle with skipping or jumping. Additionally, just 45% of the 5- to 7-year-olds can run and kick a ball, but almost 70% of 10- to 15-year-olds can perform this task. Walking and talking remains the most difficult for participants: 11% of 5- to 7-year-olds, 22% of 8- to 9-year-olds, and 22% of 10- to 15-year-olds can walk and talk at the same time.

Figure 16B explores the relationship between Inattentive ADHD classification and ability to walk and talk simultaneously, run and kick a ball, and work with music playing in the background. The bar graph compares average proficiency scores for these skills in Inattentive and non-Inattentive participants across all age groups. Both groups average at around 4 out of 5 on Likert scale for walking and talking and 2.5 out of 5 for running and kicking a ball. The non-inattentive group was slightly better at working with background music, averaging at 3 out of 5, versus the inattentive group's average of 2.3 out of 5.

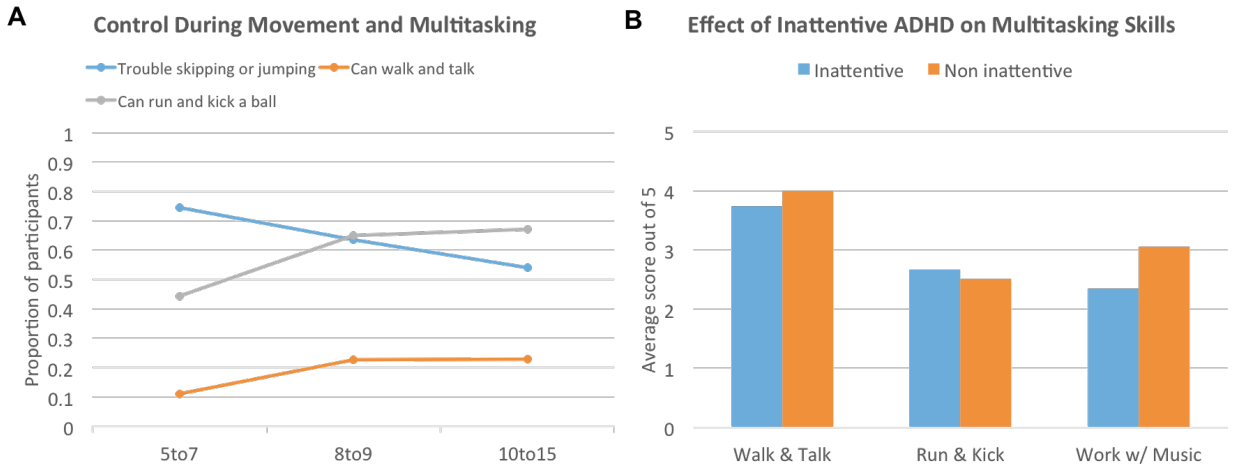


Figure 16. Progression of control during movement and multitasking
(A) This graph shows the progression of various multitasking skills. The y-axis represents the fraction of participants within each age group that can perform the task in question.
(B) The bar graph compares average competency scores (on a scale from 1 to 5) for three multitasking skills in kids who do and do not have inattentive ADHD according to the VADPRS.

Fine Motor

Fine motor skills pose a significant challenge for our participants. Figure 17 displays the acquisition of writing and typing skills in our participants. Figure 17A shows the proportion of children who can write (green), cannot write (orange), or can write a little (yellow). Over 30% of children aged 10 to 15 can only write "A little" (yellow). Almost 10% of 8- to 9-year-olds cannot write at all (orange). Children seem to begin to acquire typing skills earlier than writing skills. In Figure 17A, only 9% of children under 5 and 42% of children 5 to 7 years old can write a little (yellow). In Figure 17B, 27% of children under 5 and 55% of children 5 to 7 years old can type a little (yellow). Despite this relative delay in acquiring writing skills, fewer children can type with full proficiency by later childhood, as shown by the still-existent orange bar in the 10 to 15-year-old group in Figure 17B. By 10 to 15 years of age, all children can at least write "a little" but some children in the same age group cannot type at all.

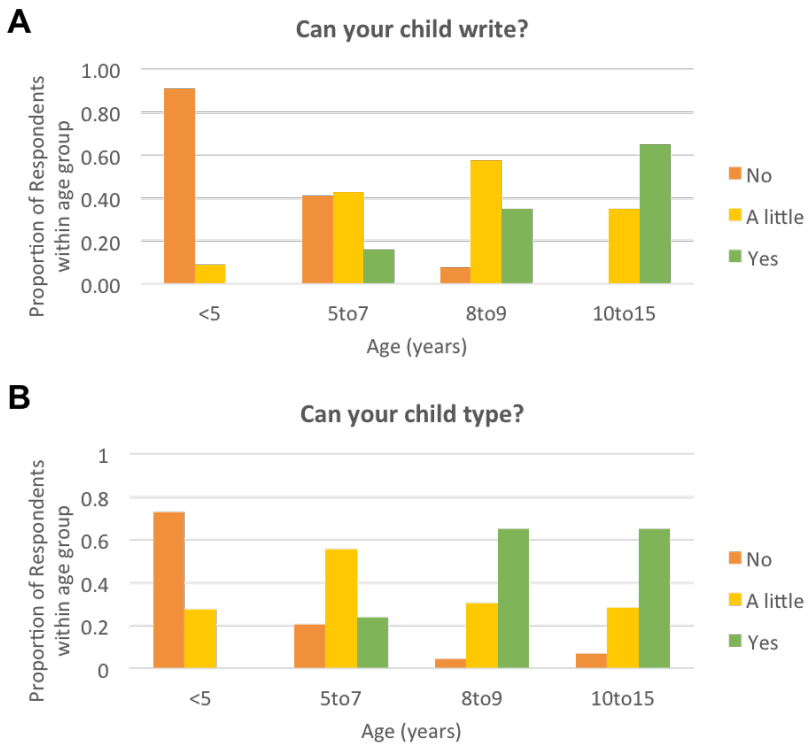


Figure 17. Acquisition of writing and typing skills
(A) By age 5 to 7, >40% of our participants still cannot write at all. By age 8to9, most children can write. The <5 age group was included to emphasize the late acquisition of fine motor skills in children with DCD.
(B) Our participants seem to acquire typing skills at an earlier age. Compare the yellow and green bars in the two graphs and you will see that before age 5, almost 30% of our participants can type a little, but only ~10% of participants can write a little.

Figure 18 shows a qualitative description of fine motor challenges. In the line graph of Figure 18A, the x axis depicts the three age groups, and the y axis represents the proportion of respondents who agree or strongly agree with the following three statements about their child's handwriting: "Slow at handwriting tasks" (blue line), "Struggled learning to write in school"(orange line), and "Finds writing extremely difficult" (gray line). The proportion of children who find writing extremely difficult increases from 56% to 69% to 85% across the three age groups. About 90% of participants within all three age groups are slow at writing tasks. The pie chart in Figure 18B shows that 93% of children find writing and using utensils difficult.

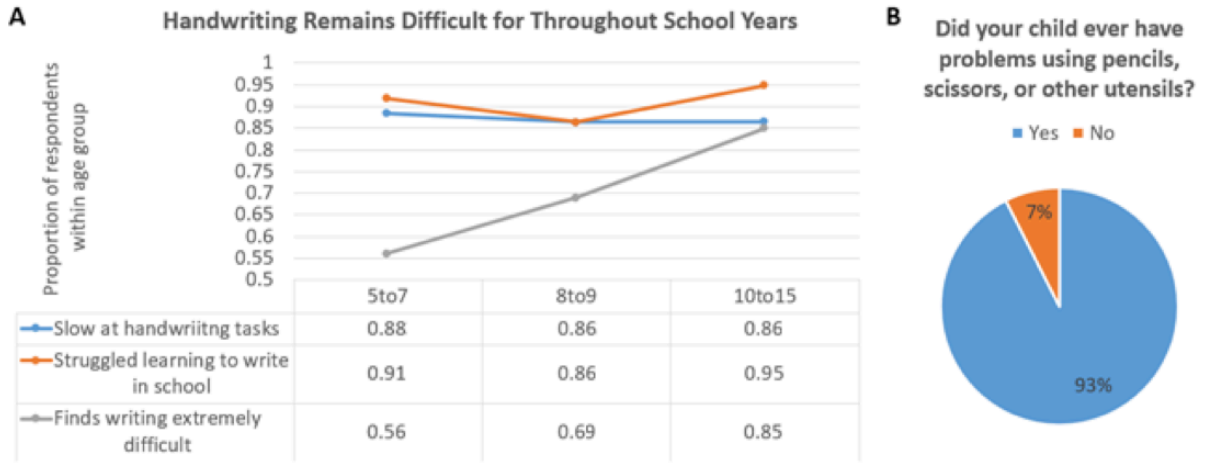


Figure 18. Handwriting challenges in Dyspraxic children
(A) This graph explores the progression of three measures of handwriting struggles across the three age groups. "Struggled learning to write in school" is high for all age groups, which makes sense since all children in our cohort are at or above primary school age. "Slow at Handwriting tasks" remains high throughout childhood, and "Finds Handwriting Challenging" increases with age.
(B) Most of our respondents reported trouble with the fine motor skill of using utensils.

Figure 19 represents a histogram of handwriting legibility across different age groups, where the color of the bars represents an age group and the x axis represents a Likert scale of legibility, ranging from 1 (Impossible to read) to 5 (Easy to read). The tallest bar of each color represents the mode – the most frequent response for each age group. Young children under 5 years of age have a mode response of "Impossible to read". The most frequent response for 10 to 15 year olds and 5 to 7 year olds is "Often hard to read" (2 out of 5 on scale), and the most

frequent response for 8 to 9 year olds is “Difficult to read for people who do not know my child’s writing patterns” (3 out of 5 on scale). There is not a single age group in which over 10% of children have handwriting that is easy to read.

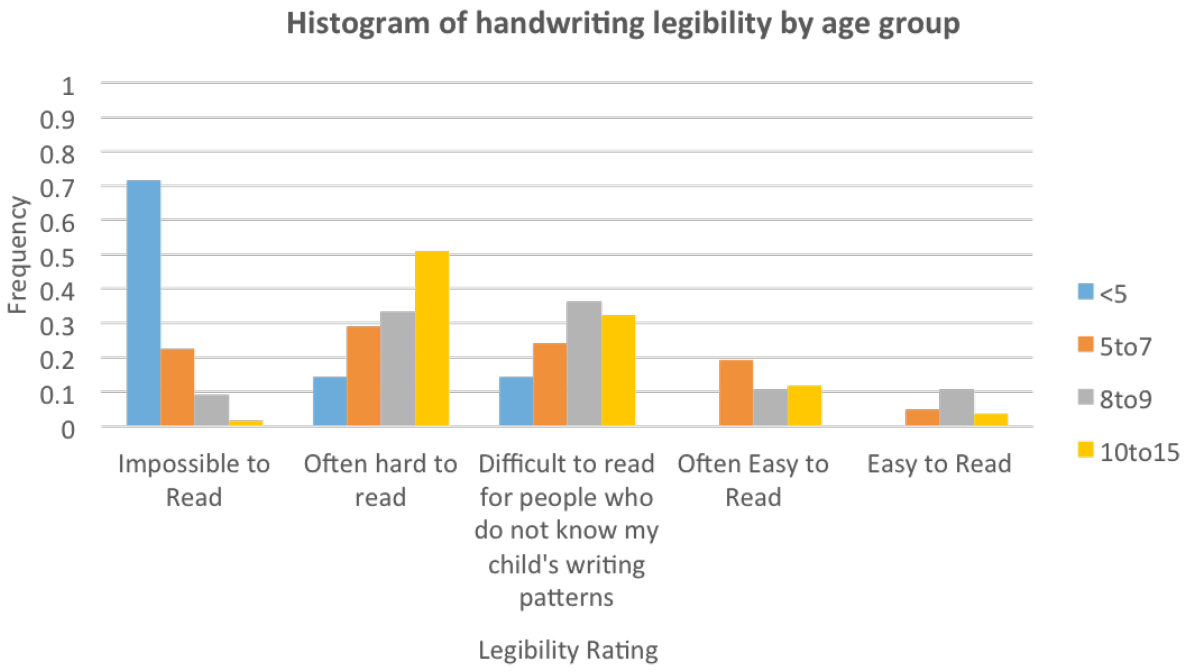


Figure 19. Legibility histogram for all age groups
This graph depicts a distribution of legibility scores for all age groups. The x axis depicts the Likert scale which the participants were using to score their children's' handwriting. The y axis represents frequency of each score within each age group. Over time the distribution gradually shifts to the right, reflecting some improvements in handwriting legibility (compare the blue and yellow curves).

General Coordination

General coordination skills, such as keeping balance when walking and completing tasks that use both hands, pose challenges for children with Dyspraxia (American Psychiatric Association). Our results fit with this description. Figure 20A shows a line graph depicting the proportion of participants within each age group who bump into things (blue line), lean on things while standing (orange line), and fall frequently (gray line). The blue and gray lines slope downward, illustrating that older children fall and bump into things less frequently than children in the youngest age group. 73% of the 5to7 group bump into things frequently, compared to 62%

of the 10to15 group. 62% of 5- to 7-year-olds, 77% of 8- to 9-year-olds, and 69% of 10- to 15-year-olds lean on things while standing. Figure 20B shows that 91% of children had trouble with bimanual activities such as buttoning a shirt. In Figure 20C, we learn that 88% had trouble learning to dress themselves.

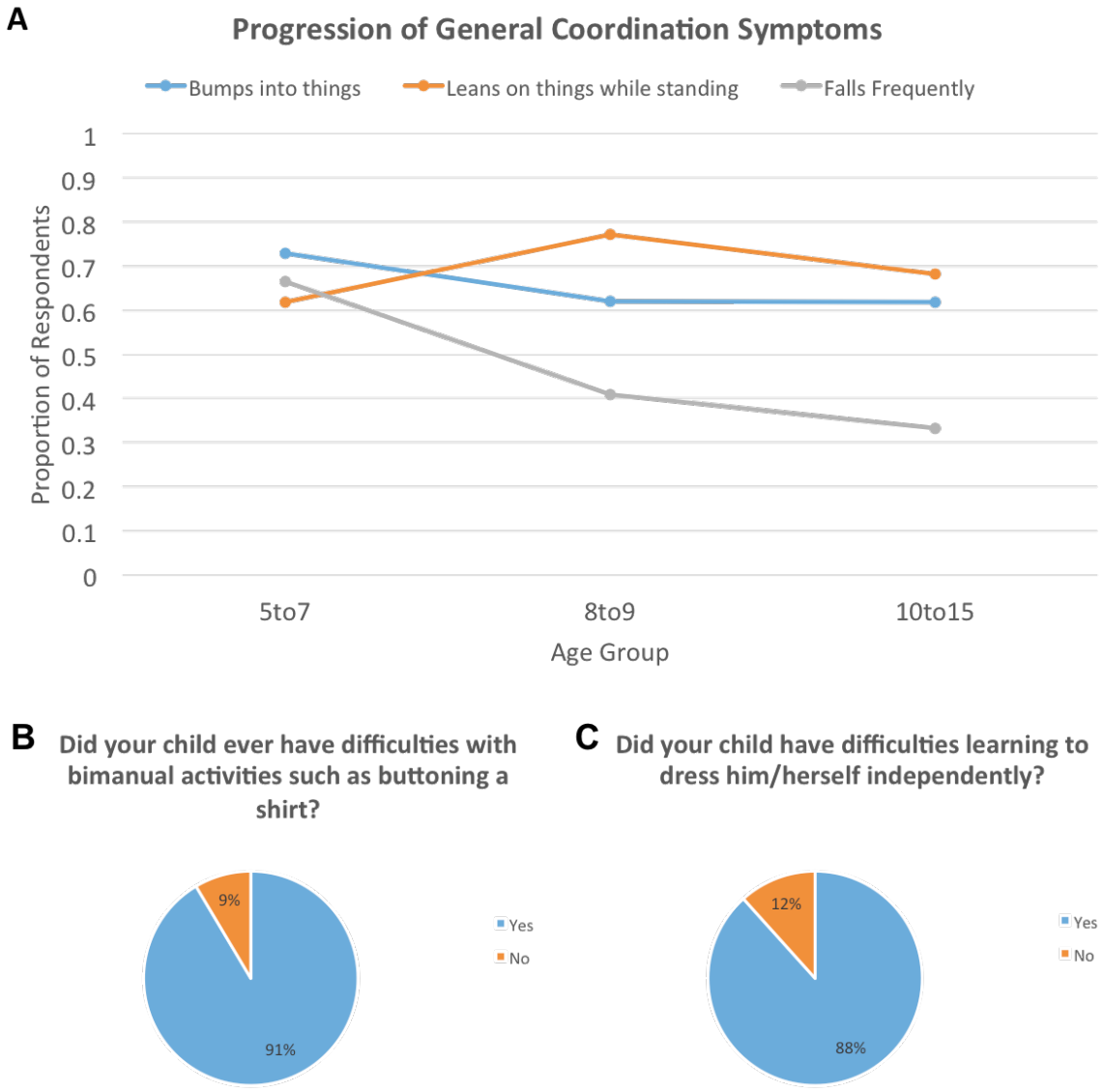


Figure 20. Characterization and progression of general coordination symptoms
(A) Line graph showing the progression of balance and coordination symptoms over the course of development. The y axis represents the fraction of participants within each age group who replied “Mostly True” or “Very True” to the three statements shown in the legend.
(B, C) Roughly 9/10 participants struggle with bimanual self-care tasks, such as getting dressed.

Early signs

In our exploration of early signs and symptoms of Dyspraxia, we focused on early motor challenges and the acquisition of motor skills. In the questionnaire, many parents described how their baby would not latch, or had trouble sucking. In Figure 21, we can see that 59% of participants noted "problems feeding, sucking or swallowing", and 49% noted "difficulty nursing or sucking". The former question is slightly broader, and in free response sections, parents described a wider range of feeding problems. For example, some spit up frequently, and others could suck, but had trouble actually ingesting the liquid, so that most of the milk or formula would end up on the infant's shirt rather than in his/her stomach. Regardless, the results show a high prevalence of feeding difficulties. In the comment sections of these questions, many respondents described how they sought the help of a lactation specialist.

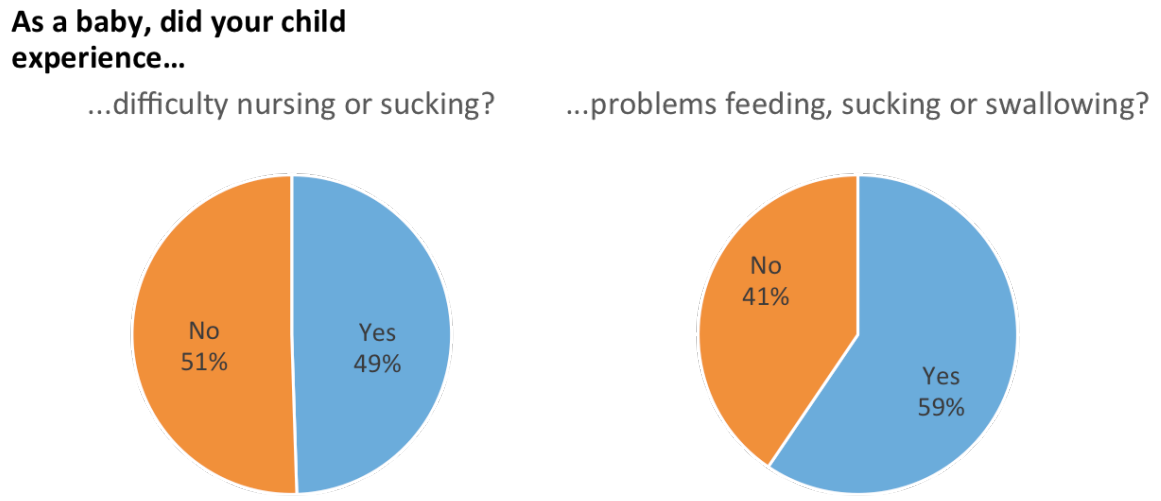
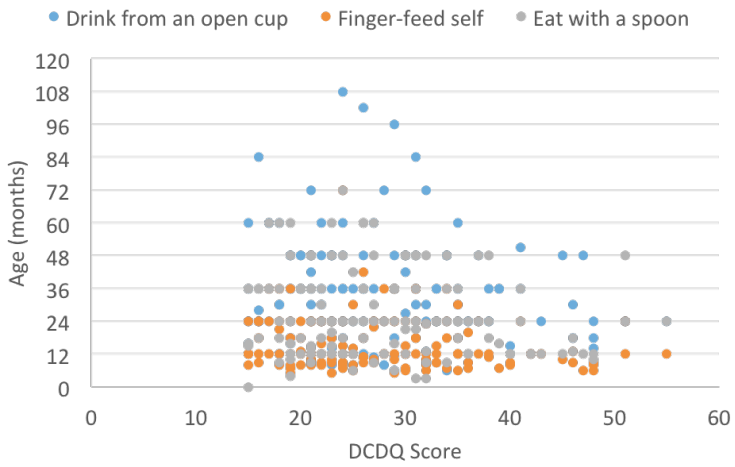


Figure 21. Early feeding signs
These two pie charts represent the proportion of participants who experiences the feeding difficulties in question. (A) Almost half of participants experienced trouble nursing. In the comments section, many respondents described how their child would not latch properly. Many participants sought the help of a nursing specialist.
(B) More participants reported problems feeding, sucking, or swallowing. In the comments section, we found reports of chronic reflux and other feeding issues beyond the motor component of nursing.

Feeding challenges continued for our participants into childhood (Figure 22). Figure 22B contains a table detailing the average age at which participants acquired the ability to drink from an open cup, eat from a spoon independently, and finger-feed themselves. Most babies are able to finger-feed themselves by 8 months of age (Rapley & Murkett, 2008), but the participants of our study did not acquire this skill until an average of 16 months of age (SD = 10 months) (Figure 22B). Participants learned to drink from an open cup eat with a spoon at an average age of 33 months (SD = 19 months) and 26 months (SD = 15 months), respectively. The high standard deviation of these statistics shows that there was large variation in the acquisition of these skills; some participants as old as eight years still were not proficient in drinking from an open cup. To see if delays in acquiring feeding skills correlated with DCDQ score, we created a scatterplot in Figure 22A. It compares each participant's DCDQ score with the age at which each participant acquired self-feeding skills. The graph reveals no significant correlation, but we do observe qualitatively that there is a greater variance in age of skill acquisition for participants with lower DCDQ scores. In other words, participants with more severe Dyspraxia symptoms (i.e., lower DCDQ scores) follow a less consistent timeline for acquiring self-feeding skills.

A



B

Skill	Average age of acquisition in months (SD)
Drink from an open cup independently	33 (19)
Finger-feed self	16 (10)
Eat with a spoon	26 (15)

Figure 22. Acquisition of Feeding Skills
(A) In this scatter plot, the y axis shows the age in months at which a participant acquired a certain feeding skill, and the x axis represents each participant's composite DCDQ score. The experimenters also generated similar scatter plots showing the relationship between feeding skill acquisition and the DCDQ subscores. However, these graphs are not reproduced here because, like present graph, there was very little correlation between the two measures.
(B) This table reports the average y value for each group of colored dots – this represents the average age of skill acquisition for each of the three measures across all participants.

We also compared "Mild DCD" and "Severe DCD", defined respectively as scoring above or below the median DCDQ score for all participants. Figure 23 compares the fraction of participants in the Mild and Severe groups who met motor milestones, including sitting up 6-8 months, rolling over before crawling, crawling by 9 months, and walking by 16 months. Around 85% of children rolled over before crawling, regardless of DCD severity. Whereas about 75% of the mild DCD group met the "Situp" milestone, only 65% of the severe DCD group met this milestone. 65% of the Mild group, compared to 40% of the Severe group, crawled by 9 months. While 82% of the Mild group walked by 16 months, just 68% of the Severe group met this milestone. We checked whether there is a difference in such motor milestones between children with mild and severe DCD (according to DCDQ score). A Chi Square revealed that the relationship between DCD severity and the achievement of walking and crawling motor milestones was only marginally significant ($\chi^2 = 7.13$, $p = 0.068$). Although the difference did not reach statistical significance, there was a trend indicating the difference in the achievement of motor milestones between the Mild and Severe groups.

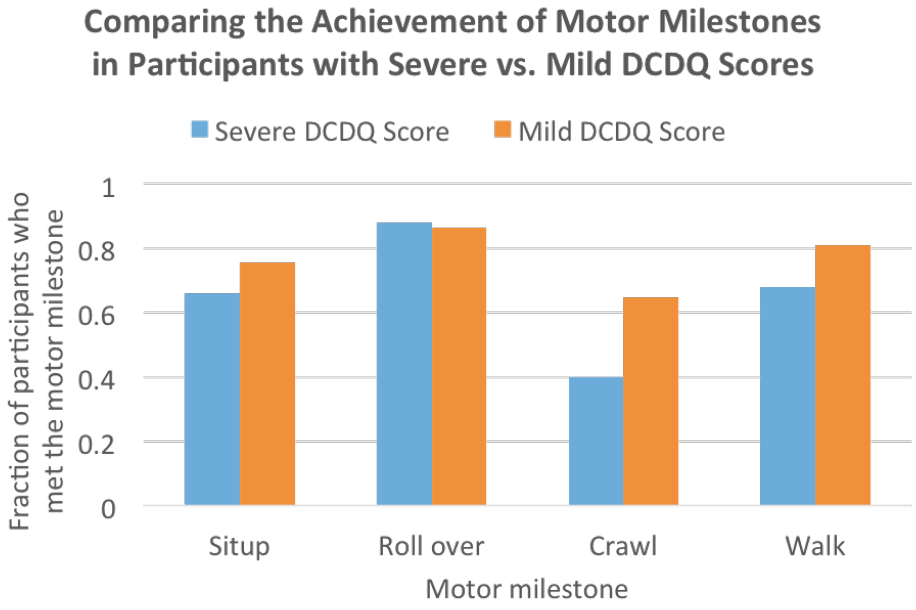


Figure 23. Motor Milestones as a potential early sign of dyspraxia
A Severe DCDQ score was any score below the median, and a mild DCDQ score was any score above the median. "Situp" = Did your child sit up by 6-8 months? "Roll over" = "Before crawling, did your child roll over?" "Crawl" = Did your child crawl by 9 months? "Walk" = Did your child walk by 16 months?

Potential Risk Factors

In our analysis of risk factors, we looked at the relationship between DCD severity, as measured by the DCDQ, and various outside influences. Because of our relatively small and homogeneous sample, our ability to draw correlations is somewhat limited, so for certain potential risk factors we simply assess prevalence. First, we were interested in prenatal and postnatal risk factors. In Figure 24, we see that prenatal stressors were more common in the mild than the severe DCD group: 48 participants in the mild group experienced prenatal medical problems and 23 experienced severe emotional stress, while 40 in the severe group experienced prenatal medical problems and 25 experienced severe emotional stress. This difference in prevalence was not significant. Prenatal medical challenges included complications such as gestational diabetes, hypothyroidism, and preeclampsia, and severe emotional stress was induced by life events such as the loss of a loved one, lost job/financial assets, and abusive relationships. Figure 24A also reports postnatal trauma, gauged by a difficult birth process and/or infant health challenges requiring intensive care. Some of these neonatal challenges included difficulties breathing, jaundice, and fever. Jaundice has been found to be more prevalent in infants later diagnosed with DCD (Hua, Gu, Jiang, Zhang, Zhu, & Meng, 2014). Figure 24B shows that 30% of infants were not born approximately to term.

A

	PRENATAL		POSTNATAL	
	Medical Problems	Severe Emotional Stress	Difficult Birth Process	Neonatal Intensive Care (e.g. NICU)
Mild DCD	48	23	55	26
Severe DCD	40	25	49	26
Most Mild DCD	24	13	30	13
Most Severe DCD	23	14	27	14

B

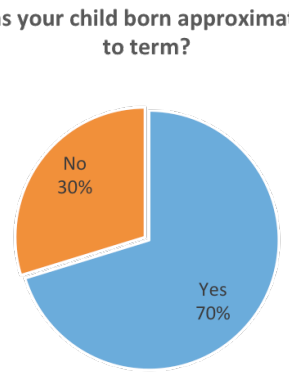
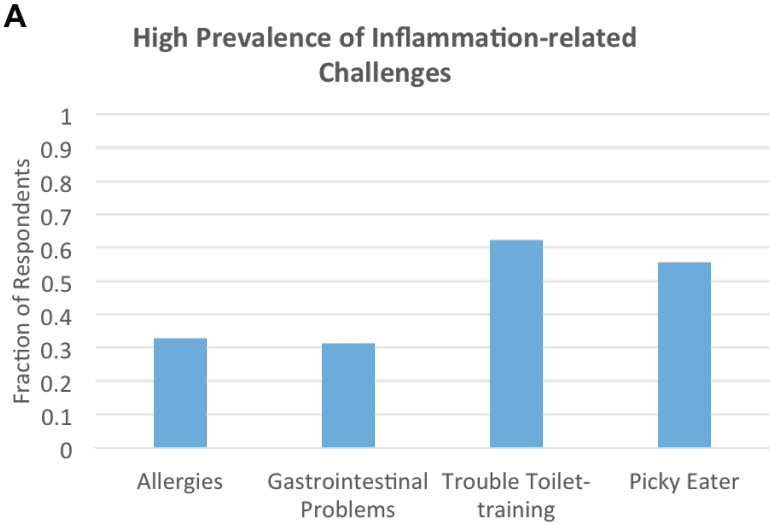


Figure 24. Prenatal and postnatal risk factors
(A) This table represents another prospective Chi square calculation. It is comparing prevalence of pre- and post-natal risk factors in the Mild DCD group vs. the Severe DCD group. Before the calculation was performed, the experimenters noted the almost identical numbers between the two groups. As expected, the Chi Square was not significant. To see if the Mild vs. Severe calculations were too broad, we narrowed our categorization to most mild and most severe, extracting data from the top 20 DCDQ scores (most mild) and the bottom 20 DCDQ scores (most severe). Once again, there was no significant difference between the groups.
(B) Across all participants, 30% of births were premature or overdue.

In Figure 25, we see that our participants show a high prevalence of inflammation-related health issues. One third of participants had allergies and/or gastrointestinal problems, and a majority were picky eaters and had problems toilet training. The gastrointestinal challenges reported ranged from constipation to inflammatory bowel disease to *Clostridium difficile.* >60% of participants had trouble toilet training, and over 50% are described as picky eaters. The subsequent correlation analysis between number of gastrointestinal problems and breastfeeding reveal that there was no significant correlation.

A



B

Gastrointestinal Problems Reported by Participants (n=63)	
Constipation	47
Diarrhea	9
Lactose intolerance	9
Reflux	5
Inflammatory Bowel Disease	4
Chronic Stomach Pain	4
Irritable Bowel Syndrome	3
Celiac disease	1
Other*	9

Figure 25. Imbalance of gut microbiota as a possible risk factor for Dyspraxia
(A) There is a high prevalence of gastrointestinal and inflammation-related difficulties in our cohort.
(B) The specific challenges faced by the participants who reported gastrointestinal problems. *"Other" included difficulties such as necrotizing enterocolitis, clostridium difficile ("C-diff"), gastritis, and Food Protein-Induced Enterocolitis Syndrome (FPIES). There was no correlation between bottle-feeding and the number of gastrointestinal problems later in life (R = 0.0547).

There was also an unclear correlation between DCDQ score and number of inflammatory challenges, as shown in the scatterplot in Figure 26. Gastrointestinal challenges considered in this analysis were: "Has your child ever had chronic or recurring Allergies?"; "Has your child ever had chronic or recurring gastrointestinal problems?"; "Is your child a picky eater?"; and "Did your child ever have difficulty with toilet training?" Children with higher DCDQ scores seem to have fewer challenges but the correlation is extremely weak.

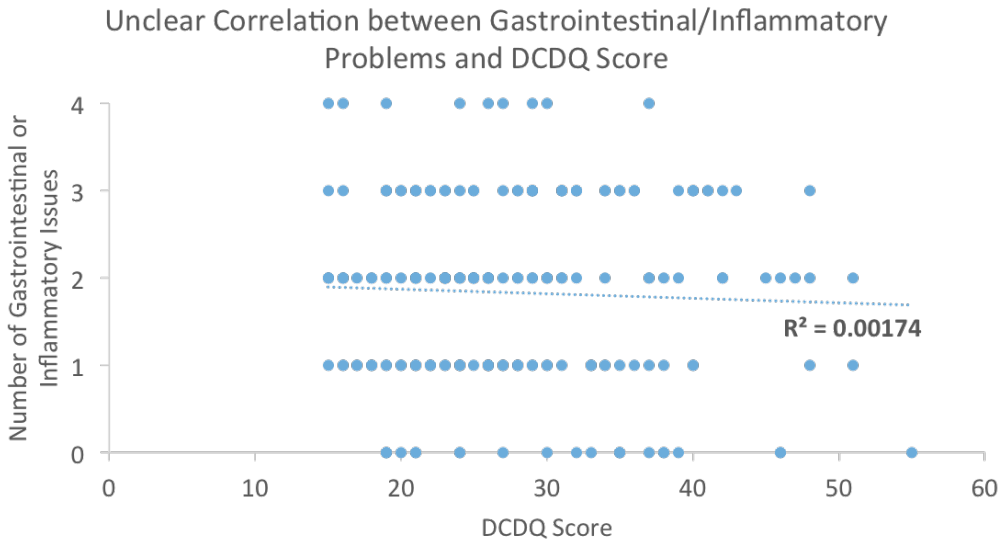
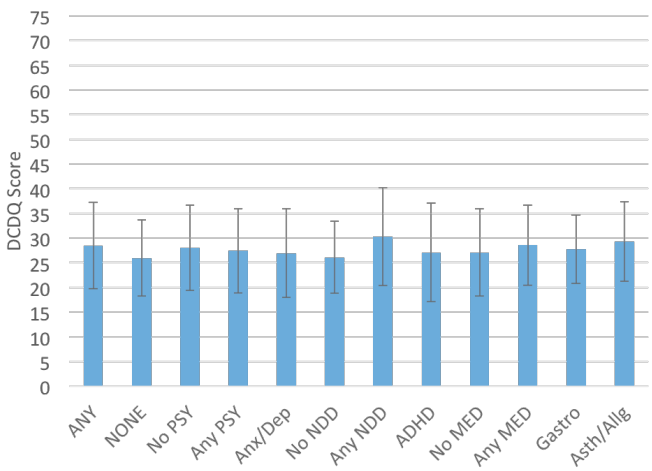


Figure 26. Unclear correlation between gastrointestinal/inflammatory problems and DCDQ Score
The y-axis in this figure represents the number of "Yes" responses to the following four questions: 1. Has your child ever had chronic or recurring Allergies? 2. Has your child ever had chronic or recurring gastrointestinal problems? 3. Is your child a picky eater? 4. Did your child have difficulty with toilet training? The x-axis is the participant's composite DCDQ Score.

Finally, to analyze genetic risk, we looked at the relationship between parent comorbidities and children's DCDQ scores. The bar graph in Figure 26A shows average DCDQ scores for participants whose parents have different comorbidities or combinations of comorbidities, as detailed in the table in Figure 26B. There here is no significant difference in DCDQ score for any combination of parent comorbidities.

A



B

Code	N	Description
ANY	154	A parent had at least one diagnosis of some kind
NONE	43	Neither parent had a diagnosis of any kind
No PSY	99	Neither parent had a psychiatric diagnosis
Any PSY	91	A parent had a psychiatric diagnosis
Anx/Dep	64	A parent suffered from anxiety or depression
No NDD	114	Neither parent had a neurodevelopmental diagnosis
Any NDD	80	A parent had a neurodevelopmental diagnosis
ADHD	35	A parent had ADHD
No MED	77	Neither parent had a medical diagnosis
Any Med	110	A parent had a medical diagnosis
Gastro	49	A parent had gastrointestinal problems
Asth/Allg	77	A parent had asthma or allergies

Figure 27. Parent Comorbidities and DCDQ Score

(A) Average DCDQ Score for different subsets of participants. The x axis specifies the subset, which is based on parent comorbidities. There is no significant difference in any set of participants.

(B) The table elaborates on the subsets depicted in the graph. The “Code” column specifies the abbreviated group name used in the graph. The “n =“ column specifies the size of the group. “Description” provides a brief description of group criteria

Discussion

The results of our questionnaire show that despite the perception that children "grow out of it" with age, Dyspraxia symptoms persist throughout childhood. In our sample of children with DCD, several patterns of symptoms and risk factors emerge: we see delayed acquisition of motor skills, persistent challenges with motor skills, and a high incidence of medical, neurodevelopmental, and psychiatric comorbidities in participants and their family members. After discussing these patterns, we will address at limitations of our study and future directions for Dyspraxia research.

In Figure 5, we looked at the pattern of neurodevelopmental, psychiatric, and medical comorbidities in participants. Our cohort showed a higher-than-average prevalence of each class of comorbidity. The high prevalence of ADHD, Dyslexia, and Speech, Language and Communication disorders is unsurprising given previous research on the frequent overlap of neurodevelopmental disorders (eg., Kadesjo et al., 2001; Pauc, 2005). The high frequency of anxiety, however, was unexpected. Given that we also found a higher-than-average prevalence of anxiety and depression in parents (Figure 4B), this relationship needs to be further explored.

The pattern of medical comorbidities was also somewhat surprising and may provide grounds for future research – why is it that Dyspraxic children show such a high incidence of inflammation-related challenges such as allergies, ear infections, and gastrointestinal problems? How does this relate to the gastrointestinal and inflammatory issues seen in ASD? (e.g., d'Eufemia, Celli, Finocchiaro, Pacifico, Viozzi, Zaccagnini,…& Giardini, 1996; de Theije, Wu, da Silva, Kamphuis, Garssen, Korte, … & Kraneveld, 2011).

In 2007, Gibbs, Appleton, & Appleton published a paper entitled, "Dyspraxia or developmental coordination disorder? Unravelling the enigma," in which the authors tried to reconcile the two diagnoses and explore the different labels and presentations of developmental movement disorders (Gibbs et al., 2007). Our Basic Medical History section shows that this enigma has not yet been unraveled. Figure 6B mentions twelve different categories of labels given to participants, and as parents' comments reveal, procuring one of these labels is a convoluted process. The geographic diversity of our participants likely contributed to diagnostic diversity, because some countries base diagnoses on the *DSM-5*, while others use the

International Classification of Diseases (ICD). However, clinicians and researchers must continue to work towards a valid and reliable definition of DCD and attempt to standardize the clinical language. Eventually, diagnosis should become an efficient and consistent process so children with DCD can gain access to early interventions.

Clinical Measures

Our Clinical Measures section shows us the average severity of DCD symptoms according to the DCDQ and the average severity of ADHD and anxiety according to the VADPRS. Both measures show mild (but insignificant) improvement in older children. This is seen as a subtle increase in DCDQ scores and slight decrease in VADPRS scores. It could be that this effect size is extremely small, and we simply need more participants to detect the difference. With a more heterogeneous participant pool, we may be able to detect more robust relationships between the DCDQ and VADPRS, which would back up previous findings that ADHD and DCD are related.

Progression of Motor Symptoms

Our results in this section confirm that children with DCD struggle with tasks such as throwing a ball, jumping, skipping, hopping, and planning movements. From the prolonged reported struggles with activities such as swimming and biking, which are considered rites of passage in many cultures, we can infer that children with coordination disorders may face specific challenges in certain social or recreational settings. The statistics presented in Figure 16 reinforce the idea that multitasking is difficult for children with Dyspraxia. Multitasking usually involves integrating information from multiple sources of sensory input. Bike riding, for example, requires the integration of visual and vestibular input; some multitasking and coordination challenges, then, may arise from sensory integration difficulties. Most of our participants are unable to walk and talk simultaneously. Another reason children with DCD struggle to multitask is because motor tasks often require their intense, explicit focus. If the cognitive load due to the motor task is already too great, this could explain why Dyspraxic children are not able to handle an additional cognitive task.

Figures 17, 18, and 19 reflect common reports in the literature of handwriting challenges in children with Dyspraxia (eg. Bo et al., 2014; Rosenblum et al., 2013). Given the demands of

school, one can imagine the challenges a 10- to 15-year-old must face if he does not know how to write, or struggles with writing. In Figure 18A, we see that that over time, an increasing number of children find writing extremely difficult. This could be due to the increasing difficulty and quantity of writing tasks throughout the course of school. Alternatively, it could reflect an increased reliance on assistive technology such as a scribe or keyboard. Much work has been done characterizing the handwriting impairments of children with DCD (e.g., Bo et al., 2014; Ghanizadeh, 2010; Rosenblum et al., 2008). Researchers must continue to explore effective intervention strategies to close the gap in writing skills.

General coordination reflects a child's movement efficiency, general muscular endurance, and ability to learn motor sequences. Activities that require coordination usually involve crossing the midline. One of the first coordinated actions is crawling, and we found in the comment sections that several participants never crawled at all, or scooted instead of crawling. In Figure 18A, notice how the blue and gray lines (representing the frequency of "Often bumps into things" and "Falls frequently") slope downward, but there is a slight increase in the frequency of "Leans on things while standing". Leaning on other objects may reflect a compensation technique. Over the years, children fall down less frequently, but still rely on other objects to help them maintain balance. Compensation is a commonly noted phenomenon in neurodevelopmental disorders and may be one reason why disorders like Dyspraxia are not widely recognized in adult populations. In childhood, many individuals struggle with adaptive behaviors such as getting dressed, brushing their teeth, walking, yet over time, children adapt to their deficits. This process of adaptation and problem solving is worth exploring. Future interventions may focus on cognitive flexibility and problem solving skills.

Early signs

Earlier diagnosis will facilitate early intervention, and pinpointing the earliest signs of Dyspraxia may help uncover the etiology of the disorder. According to some reports, up to 35% of all infants experience feeding problems (Arts-Rodas & Benoit, 1998). These problems have been shown to be especially prevalent in children with ASD (e.g., Keen, 2008; Field & Williams, 2003) and other neurodevelopmental disorders (Degangi, Breinbauer, Roosevelt, Porges, & Greenspan, 2000). Degangi et al. (2000) found that 95% of infants who experienced problems with self-regulation (such as sleep, feeding, self-calming, and sensory reactivity) were found at

age 3 to have motor, language, or cognitive delays, or parent-child relational problems (Degangi et al., 2000). 50-60% of our participants experienced feeding problems during infancy.

Feeding challenges in our participants continue beyond the nursing stage. In Figure 20, we reported the age at which participants acquired self-feeding skills, such as the ability to drink from an open cup independently. Though there is no clear correlation between the age of acquiring these skills and DCDQ score, our cohort as a whole learned self-feeding skills later than reported US national averages. In future studies, it would be productive to compare these statistics with a typically developing population. If there is a significant difference between the groups, this will provide a useful and easily recognizable sign that parents can identify in their children. "Motor milestones" provide a similarly useful sign of motor development in children. We found that participants with the lowest DCDQ scores (severe DCD group) missed the crawling and walking milestones more frequently than participants with higher DCDQ scores.

Risk Factors

Although we did not achieve significant results in our correlational analyses in this section, we can make important inferences by looking at our cohort as a whole. In Figure 24, we explored prenatal and postnatal risk factors. In our participants, there was a high incidence of premature birth, medical problems, and severe emotional stress during pregnancy. A population-based study of DCD over 4,000 Chinese children found significant correlations between Dyspraxia and similar prenatal factors including: fetal distress, threatened abortion during early pregnancy, high maternal age, preterm birth, and newborn pathological jaundice (Hua et al., 2014).

In addition to prenatal and postnatal risk factors, our cohort reported a high prevalence of inflammatory and gastrointestinal challenges. Recent work exploring the link between neurological disease and inflammation suggests that inflammatory factors compromise the blood-brain barrier, exposing the brain to injury (Stolp et al., 2009; Theoharides & Zhang, 2011). Over the past 40 years, hundreds of studies have provided evidence that Autism Spectrum Disorder (ASD) is associated with inflammation or immune dysregulation (Rossignol & Frye, 2012). The link between inflammation and neurological disorders is still being explored, but our results support the hypothesis that inflammatory problems and neuropathology are related. If our

diet influences our microbiome, and our microbiome influences the amount of inflammation our body experiences, diet could offer an indirect means of alleviating inflammation-related neuropathology. Could DCD be managed with diet?

Lastly in our Risk Factors section, we discuss genetic correlations between DCDQ score and parent comorbidities. Figure 27 shows that parent comorbidities have a negligible effect on DCDQ scores. This may change, however, with a more diverse cohort.

Limitations

The two major limitations of our study are lack of a control group and small sample size. A control group would have been useful in the Early Signs and Possible Risk Factors sections. In these domains, we were searching for correlations between different independent variables and presence or absence of DCD, as well as severity of DCD according to the DCDQ. Almost every single one of our participants qualified as Dyspraxic, and the average scores were far below the DCDQ cutoffs. To draw correlations between, for example, number of gastrointestinal issues and DCDQ score, it would be more productive if we had participants with a broader range of DCDQ scores. This would also provide us with a clinically valid comparison group–DCD and non-DCD–rather than the somewhat arbitrary "Severe DCD" and "Mild DCD" groups which were used in the motor milestones analysis.

A larger sample size would also make our study stronger. We started out with ~250 responses, but many of these were incomplete. After excluding incomplete responses, we were left with 191 participants. This number varied, though, for every single question; the consent form was the only mandatory portion of the questionnaire, and many participants did not fill out some questions. The Chi Square analysis comparing missed walking and crawling milestones in Mild vs. Severe DCD groups (Figure 21B) yielded a p value of 0.068. It could be that we are trying to detect a small effect size here, and that with more participants, this difference would become significant. In our analyses involving the change or progression of a skill over time, (e.g., Figures 15, 16A, 17), we were forced to use the age groups defined by the DCDQ (5 to 7, 8 to 9, 10 to 15, and where appropriate, <5). With more participants, we would be able to analyze the progression of motor symptoms for smaller age ranges. We could then get more detailed information about the progression of various symptoms.

Future Directions

The present study addresses just a fraction of our Dyspraxia Questionnaire, but we can use its results to inform future data analysis. One of our most interesting findings was the overlap of ADHD and DCD. Since we have found that inattention and dyspraxia co-occur, the next step will be to explore the inattentive Dyspraxic phenotype. A future study will elaborate on basic medical history and report medication use, because upon observation, it seems many of our participants take methylphenidates, a common pharmaceutical treatment for ADHD. Because both ADHD and DCD are implicated with sensory processing difficulties, we will also analyze questions about sensory processing. Integrating information about time, space, textures, scenes, and sounds is a complex process that appears to be disrupted in many neurodevelopmental disorders. With data we have already collected, we will be able to analyze the prevalence and progression of sensory processing challenges in children with DCD and DCD+ADHD. Patterns of deficits or sensitivities will show us which forms of sensory processing challenges are common in both disorders, and which are specific to DCD or ADHD. These patterns will provide clues to the etiologies of these disorders.

Since we found a high prevalence of anxiety in our participants, it will be important to learn more about the psychosocial experience of having DCD. What kinds of support systems are most important for a child to have in his early school years? How does DCD affect his social life? In questionnaire we asked about participants' temperament, social life, and measures of wellness such as quality of sleep. The investigation of the psychosocial side of DCD will help us better understand what support systems these children need. In addition, we may be able to draw distinctions between ASD and DCD in this investigation, by looking at patterns of social function and emotional responses.

After we have sufficiently mined the Questionnaire data, we can design abbreviated questionnaires addressing specific unanswered questions. Shorter questionnaire could be distributed to more participants – including the parents of neurotypical children – and analyzed more quickly. If we include some of the same questions, we could even compile our data sets and conduct more statistically powerful analyses. We could then draw stronger conclusions about the correlation between Dyspraxia outcome and risk factors, early signs, and comorbidities.

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