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ORIGINAL ARTICLE

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Prevalence and pattern of executive dysfunction in school age children with congenital heart disease

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Abstract

Objective: Executive function, a set of cognitive skills important to social and academic outcomes, is a specific area of cognitive weakness in children with congenital heart disease (CHD). We evaluated the prevalence and profile of executive dysfunction in a heterogeneous sample of school aged children with CHD, examined whether children with executive dysfunction are receiving school services and support, and identified risk factors for executive dysfunction at school age.

Design: Ninety-one school aged patients completed questionnaires, including the Behavior Rating Inventory of Executive Function (BRIEF) and a medical history questionnaire. An age- and gender-matched control sample was drawn from a normative database.

Results: Children with CHD had a higher rate of parent reported executive dysfunction (OR = 4.37, $P < .0001$), especially for working memory (OR = 8.22, $P < .0001$) and flexibility (OR = 8.05, $P < .0001$). Those with executive dysfunction were not more likely to be receiving school services ($P > .05$). Gender, premature birth (≤37 weeks), and CHD with aortic obstruction were predictive of executive dysfunction, especially for behavior regulation skills.

Conclusions: School aged children with CHD have an increased prevalence of executive dysfunction, especially problems with working memory and flexibility, and are underserved by the school system. The increased risk for executive dysfunction in those with CHD and prematurity or CHD with aortic obstruction suggests an etiology of delayed brain development in the fetal and neonatal periods, while male gender may increase susceptibility to brain injury. This study highlights the need for regular neurodevelopmental follow up in children with CHD, and a need to better understand mechanisms that contribute to adverse neurodevelopmental outcomes.

KEYWORDS
congenital heart disease, executive function, neurodevelopment, outcomes

1 | INTRODUCTION

As survivorship has improved for children with complex congenital heart disease (CHD), emerging research shows that children with CHD are at high risk for neurodevelopmental problems.[1,2] There are abnormalities in brain maturation and brain injury that are present in infancy, even prior to surgical intervention.[3–6] Neurodevelopmental problems in CHD are thought to be related to disrupted fetal and neonatal brain development and subsequent increased susceptibility to brain injury.[7] MRI abnormalities have been found in older children and adolescents with CHD,[8] and are associated with cognitive impairments.[9] Population based studies suggest children with CHD access special education services at a higher rate than those without CHD.[10] In addition, the rate of children needing educational assistance increases over the course of development, and though most children have normal intellectual functioning, there are problems with attention, executive skills, memory, visual-spatial skills, and social/pragmatic language skills.[8,11–13]

Previous studies document a range of outcomes in children with CHD, but there are limitations in what they address. First, many examine only specific cardiac diagnoses, or divide children into smaller groups by cardiac diagnosis. This limits the ability to evaluate specific disease factors as they relate to outcome. For example, single ventricle defects and CHD with aortic obstruction likely alter the fetal circulation, affecting fetal brain development,[14] and subsequently may impact cognitive outcomes. Second, many studies primarily address outcomes in infants or toddlers.[15–17] Some studies extend into school age and adolescence,[8,12,13,18–21] but few take into account the aspects of a child's medical or demographic profile that may predict a specific cognitive outcome beyond surgical factors and IQ. There is some suggestion that the severity of the defect as indicated by postnatal cyanosis, need for single ventricle palliation, or CHD with aortic obstruction, along with other medical complications such as seizures, stroke, abnormal neurological examination, abnormalities on MRI, premature birth, extended hospital stay, or use of mechanical support, incur higher risk for neurodevelopmental consequences.[2] This study addresses gaps in the extant literature by examining a heterogeneous sample of children with CHD requiring surgical repair in the first year of life, and by examining specific aspects of a child's disease as predictors, rather than dividing children into diagnostic subgroups a priori.

Executive functioning (EF) has been identified as a specific area of cognitive impairment in CHD that is critical to social development and academic learning.[8,12,22–25] EF describes a set of behaviors responsible for purposeful, goal directed activity.[26] It is used to organize and direct cognitive activity, emotional responses, and overt behavior. Developmentally, these skills emerge in toddler/preschool years and develop substantially through childhood, adolescence and early adulthood, mirroring increasing environmental demands. Given this, difficulties in EF become more apparent over time. Children with executive dysfunction are often overlooked by general practitioners and schools, as intellectual development can be unrelated to executive skills problems, or problems with executive skills may be masked by stronger intellectual skills on some testing.[27,28] Despite this, executive dysfunction is strongly related to a child's development, learning, behavior, and academic success, and it has been suggested that EF is a better predictor of classroom performance and academic achievement than intellectual or early academic skills.[29,30] In this way, it is possible that school age children with CHD who would potentially qualify for accommodations and/or services are being under identified.

The aims of this study are to (1) evaluate the prevalence and profile of executive dysfunction in a heterogeneous sample of school aged children with CHD, (2) to examine whether school aged children with executive dysfunction are receiving school services and supports, and (3) to identify which indicators of medical severity represent risk factors for executive dysfunction. We hypothesize that children with CHD are at high risk for executive dysfunction at school age, and given previous reports we expect a high prevalence of impairment in this area. In addition, we hypothesize that those patients whose cardiac defect is more likely to alter the fetal and neonatal brain circulation or which predisposes to hypoxic injury (e.g., single ventricle defects, CHD with aortic obstruction, or cyanosis), and those with more complicating medical factors (such as neurological events or prematurity) will have increased prevalence of executive dysfunction.

2 | METHODS

2.1 | Participants and procedures

Children with CHD were recruited via social media (Facebook posts in CHD specific groups), in-hospital advertisements, and at cardiology or neuropsychology clinic visits. Patients were included if they had CHD requiring open heart surgery within the first year of life. Patients were excluded if they were diagnosed with a genetic syndrome that would better explain their cognitive and behavioral profile, or if they had a substantial, identified genetic finding that was presumed to have a large influence across organ systems. Study procedures were approved by the Institutional Review Board at Children's National Health System. Parents gave written informed consent, children between 7 and 10 years of age provided verbal assent to participate, and children over 11 years of age provided written assent to participate. As part of the informed consent process, participants gave permission to contact the child's cardiologist for a recent clinic note, which was used to confirm cardiac diagnosis.

Parents completed a set of questionnaires that were delivered and returned by mail or in person. Study data were collected and managed using REDCap.[31] This included a demographic and medical history questionnaire, where parents reported any prior neurological findings (including presence of MRI abnormalities if MRI was available, abnormal EEG, nonfebrile seizures, or stroke), pregnancy/birth history, and other information on their child's medical and educational history. The Behavior Rating Inventory of Executive Function (BRIEF) is a standardized questionnaire completed by the primary caregiver or parent that has been widely used in research and clinical settings to assess the presence and severity of executive dysfunction in day to day situations.[32] It is composed of three broad indices (General Executive Composite, the Metacognitive Index, and the Behavior Regulation Index) and eight subscales. The metacognitive index is comprised of five subscales; initiate (how well an individual independently initiates tasks), working memory (holding information in mind, manipulating information in mind), planning/organization (using systematic, well planned approaches to tasks), organization of materials, and monitor (monitoring one's behavior, or task approach). The Behavior Regulation Index is comprised of three subscales, including inhibit (an index of impulsive behavior or acting before thinking), shift (the ability to maintain a flexible approach to problem solving or behavior), and emotional control (the ability to manage and regulate emotional responses). Age-based T-scores are computed for each subscale and index, and a score of 65 or higher is considered a clinically significant problem. To examine the prevalence of parent reported executive dysfunction, we classified each subject's scores on subscales as clinically elevated ($T \geq 65$) or not elevated. In addition, an age- and gender-matched control sample was drawn from the normative database for the BRIEF for statistical

TABLE 1 Diagnoses and classifications of the obtained sample

Classification	Frequency by diagnosis, $N = 91$
Class 1 2V, no aortic obstruction 37 Total	6 Dextro-transposition of the great arteries and intact ventricular septum 3 Dextro-transposition of the great arteries and ventricular septal defect 6 Tetralogy of Fallot 5 Tetralogy of Fallot/pulmonary atresia 4 Truncus arteriosus 4 Ventricular septal defect 3 Atrioventricular canal defects 6 Other 2V defects
Class 2 2V, aortic obstruction 15 Total	1 Truncus arteriosus (with Interupted aortic arch) 2 Ventricular septal defect with coarctation 3 Coarctation/arch hypoplasia 9 Other 2V defects with aortic obstruction
Class 3 SV, no aortic obstruction 19 Total	4 Pulmonary atresia with intact ventricular septum 15 Other functional SV defects
Class 4 SV, aortic obstruction 20 Total	13 Hypoplastic left heart syndrome 7 Other functional SV defects with aortic obstruction

2V, two ventricle; SV, single ventricle.

comparisons as described in detail below. In order to reduce the number of statistical tests performed, while retaining detailed information about executive skills profiles, only subscale scores were entered into analyses, as the indices are directly derived from the subscales and would provide overlapping information.

Each patient was assigned to one of four previously described diagnostic classes[33]: Class I—two ventricle CHD without aortic obstruction, Class II—two ventricle CHD with aortic obstruction, Class III—single ventricle CHD without aortic obstruction, or Class IV—single ventricle CHD with aortic obstruction. Table 1 presents the specific diagnoses in each cardiac class. CHD Class was determined by the study cardiologist (MTD) based on the information given in the history form and/or the medical records. Any CHD diagnosis which included aortic valve stenosis or coarctation, hypoplasia, or interruption of the aortic arch was considered to have aortic obstruction. Single ventricle palliation versus two ventricle repair was determined by the type of surgical repair undertaken. Cyanosis was coded based on specific diagnosis and anticipated postnatal clinical presentation. Given that the number of patients in each class was too small for multivariate analyses of individual diagnostic classes, subjects were instead compared based on important physiological components of their cardiac diagnosis, including single ventricle (Class III and IV) vs. two ventricle (Class I and II) repair, CHD with aortic obstruction (Class II and IV) vs. no aortic obstruction (Class I and III), and lesions with postnatal cyanosis versus acyanotic. Based on parent report and available records, classifications were also made for medical risk variables, including prematurity (≤37 weeks gestation), and the presence of neurological abnormality (the presence of *any* of the following by parent report/records: stroke, seizures, MRI, or EEG abnormality).

2.2 | Statistical analyses

Fisher's exact tests were used to determine whether parents of children with CHD were more likely to report elevations across subscales of the BRIEF relative to controls drawn from an archival database. Fisher's exact tests were also used to evaluate whether children with elevated BRIEF subscale scores were more likely to be receiving special education services or supports. Multivariate logistic regression models were then implemented to examine the odds of elevation in each of the BRIEF subscales in relation to available medical and demographic risk variables (single/two ventricle, cyanosis, aortic obstruction, presence of any neurological abnormality, prematurity [≤37 weeks/full term], and gender). An effect was considered statistically significant if P value in a 2-tailed test was less than .05. Cyanosis was not included in the models as our preliminary analysis suggested it did not significantly contribute to the models.

3 | RESULTS

3.1 | Prevalence of executive dysfunction

Ninety-one children with CHD (mean age 9.08 years, SD = 2.71, range 6-17; 53 male) participated in the study. The sample was a combination of clinically referred patients that volunteered to participate in the study ($n = 26$), a local sample that volunteered for a research appointment ($n = 15$), and volunteers from around the country who completed questionnaires by mail ($n = 50$). Ninety-one age- and gender-matched controls with data on the BRIEF questionnaire were drawn from the normative database from the BRIEF. Descriptive data for each group are presented in Table 2.

There was a high prevalence of parent reported executive dysfunction in our sample, with 64.8% of parents reporting at least one elevation on the BRIEF, compared with 29.7% of controls (odds ratio = 4.37; 95% CI: 2.35, 8.14, $P < .0001$). Figure 1 and Table 3 show the percentage of the sample with clinically significant elevations by subscale. Parents of children with CHD were more likely to endorse clinically significant elevations across BRIEF subscales (all $P < .05$, Table 3), except for Inhibit ($P = .07$, Table 3). Working Memory and Shift were most frequently endorsed as problematic, with parents of children with CHD being over eight times more likely to endorse a problem than parents of healthy controls.

3.2 | Access to services

Thirty-three percent of children with CHD were receiving some form of support in the school setting (such as an IEP, 504, or similar student support plan if in a private school setting). Those children with CHD who had at least one area of executive dysfunction were not more likely to be receiving services in the school setting when compared with those who did not endorse any problems (χ^2 (1, $N = 91$) = .044, $P = .833$). Similarly, the odds of receiving services or supports in the school setting were not significantly higher for children with CHD endorsing problems in any specific area of EF (Table 4), though there

TABLE 2 Descriptive statistics for CHD and controls on the BRIEF

Indices/subscales	Controls	All CHD	Class I	Class II	Class III	Class IV
Metacognitive index	51.98 (9.84)	59.43 (12.23)	58.30 (12.11)	63.07 (14.00)	58.95 (13.36)	59.25 (15.11)
Initiate	50.05 (9.31)	57.84 (11.95)	56.08 (12.13)	61.60 (12.87)	57.32 (13.68)	58.75 (8.95)
Working memory	51.77 (9.82)	60.88 (11.95)	59.97 (11.42)	63.33 (11.90)	60.32 (14.52)	61.25 (10.90)
Planning/organization	51.21 (10.03)	58.70 (12.69)	57.81 (12.30)	60.47 (15.44)	59.00 (13.87)	58.75 (10.71)
Organization of materials	49.46 (9.48)	55.41 (11.37)	55.51 (10.91)	59.07 (14.27)	52.32 (10.05)	55.40 (11.00)
Monitor	53.92 (10.72)	56.91 (12.38)	55.57 (13.49)	59.40 (12.67)	58.21 (12.15)	56.30 (10.59)
Behavior regulation index	50.54 (9.43)	57.55 (14.67)	55.84 (14.75)	61.53 (16.37)	55.89 (12.00)	59.30 (15.78)
Inhibit	52.22 (9.90)	54.95 (14.22)	54.95 (15.10)	57.40 (13.97)	52.68 (12.28)	55.25 (15.11)
Shift	48.89 (9.07)	58.13 (14.74)	54.76 (12.52)	60.07 (18.00)	60.95 (13.07)	60.25 (17.14)
Emotional control	50.44 (9.68)	57.19 (14.23)	55.38 (14.20)	62.80 (16.65)	53.95 (12.24)	59.40 (13.00)

Results are mean *T*-scores for each scale, mean = 50, standard deviation = 10. A *T*-score ≥65 is considered a significant elevation.
BRIEF, Behavior Rating Inventory of Executive Function; CHD, congenital heart disease.

was a trend toward children with inhibitory control problems being more likely to receive services.

3.3 | Relationship between medical/demographic risk factors and executive dysfunction

Results of the multivariate logistic models are presented in Table 5, in which the *P* values of Hosmer and Lemeshow Goodness-of-Fit Tests are all statistically insignificant ($P > .05$), indicating that all logistic regression models fit the data very well. Prematurity showed the strongest impact on executive dysfunction in children with CHD, especially with respect to behavioral regulation, with significantly increased risk for elevated scores on the Inhibit and Emotional Control subscales, and increased risk on Initiate and Working Memory scales relative to full-term children with CHD. The presence of CHD with aortic obstruction significantly increased risk for elevated scores on the Emotional Control and Organization of Materials scales. Male gender was associated with increased risk for elevated scores on the Inhibit, Shift, Monitor, and Planning/Organization scales. Contrary to our hypothesis, children with single ventricle defects were not more likely to experience executive dysfunction. In fact, children with two ventricle CHD were *more* likely to have problems with Emotional Control (OR = 3.53, 95% CI: 1.02, 12.15) and Organization of Materials (OR = 3.75, 95% CI: 1.23, 11.45). The presence of neurological abnormalities was not associated with executive dysfunction for children with CHD.

4 | DISCUSSION

This study reveals a high prevalence of executive dysfunction in a sample of school age children with CHD requiring surgery in the first year of life. In the group as a whole, problems with working memory (mental maintenance and manipulation of information) and flexibility (rigid behavior and patterns of thinking) were most commonly reported. This pattern and prevalence of parent reported executive dysfunction is similar to previous reports.[23] Several aspects of a child's medical history and gender were associated with increased risk for executive dysfunction, especially for behavioral dysregulation.

Overall, prematurity was the strongest predictor of negative outcomes for both metacognitive skills and behavior regulation, followed by male gender and CHD with aortic obstruction. We propose that these medical and demographic risk factors may increase the risk for executive dysfunction by impacting brain development in the fetal and neonatal period. Neurodevelopmental problems in CHD are thought to be related to delayed fetal and neonatal brain development and subsequent susceptibility to brain injury.[7] At term, some neonates with CHD have brain MRI findings similar to those of premature infants born at 35 weeks gestation.[4] Risk factors identified in this study impact fetal circulation, which is thought to be a primary mechanism of these maturational changes and subsequent injury. That is, the aortic obstruction may contribute to decreased antegrade flow in the ascending aorta in fetal life, thus likely contributing to delayed brain maturation in-utero.[34] Prematurity also impacts brain maturation and susceptibility to injury. In fact, executive dysfunction has been identified as a specific area of concern in premature children.[35–37] Given this, our data suggest that prematurity further impacts brain maturation in children with CHD, and therefore subsequent susceptibility to injury. Comparison to children with prematurity and no CHD would provide greater insights into the contribution of each risk factor and their cumulative effects.

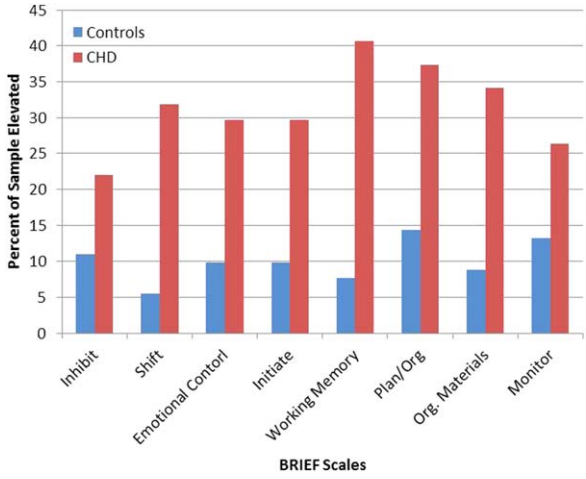

FIGURE 1 Prevalence of executive dysfunction: percent of the sample reporting clinically significant elevations (*T* score ≥ 65) on the BRIEF.

TABLE 3 Comparisons of clinically elevated BRIEF scores in children with CHD versus controls

Indices/subscales	% Elevated scores: Controls *N* (%)	% Elevated scores: CHD *N* (%)	Odds ratio	95% CI	*P* value*
Metacognitive index					
Initiate	9 (9.9%)	27 (29.7%)	3.84	1.69, 8.75	.0013
Working memory	7 (7.7%)	37 (40.7%)	8.22	3.42, 19.77	<.0001
Planning/organization	13 (14.3%)	34 (37.4%)	3.58	1.73, 7.39	.0006
Organization of materials	8 (8.8%)	31 (34.1%)	5.36	2.30, 12.48	<.0001
Monitor	12 (13.2%)	24 (26.4%)	2.36	1.10, 5.07	.0397
Behavior regulation index					
Inhibit	10 (11%)	20 (22%)	2.28	1.00, 5.20	.07
Shift	5 (5.5%)	29 (31.9%)	8.05	2.95, 21.95	<.0001
Emotional control	9 (9.9%)	27 (29.7%)	3.84	1.69, 8.75	.0013

Note: * Fisher's exact test.
BRIEF, Behavior Rating Inventory of Executive Function; CHD, congenital heart disease.

Finally, males may be more vulnerable to problems associated with brain immaturity, specifically to neonatal hypoxic-ischemic injury.[38] Males and females are known to respond differently to neonatal hypoxic-ischemic injury, which may explain gender differences in prevalence for central nervous system disorders such as cerebral palsy.[39] In addition, there may be different neuronal pathways for cell death in males and females,[40] and estrogen may be neuroprotective.[41]

Interestingly, children with single ventricle CHD were not more likely to have executive dysfunction at school age than children with two-ventricle repair. In fact, children who underwent two ventricle repair in this study group were at increased risk for problems with emotional control and organization. This result suggests that all children with CHD, including those who have a two-ventricular repair should be considered at risk for neurodevelopmental abnormalities. Since surgical and medical management of single ventricle patients is generally more complex, and since they may have more physiological complications,[42,43] practitioners and researchers often assume that they will have worse neurocognitive outcomes across domains. Indeed, while some studies show worse performance on global outcomes, such as IQ,[44] these findings only approach statistical significance when other patient specific factors are taken into account. That is, it may be that examination of these patient specific factors (e.g., specific physiological complications, specific disease-related factors such as aortic obstruction or other associated complications such as prematurity) may eventually explain more of the variance, and provide clues regarding mechanisms of action. Additionally, studies do not often look beyond coarse outcomes such as IQ to specific cognitive skill areas or profiles, or at times they focus exclusively on single ventricle patients[15,45] or other specific diagnostic groups, such as transposition of the great arteries.[12] Instead, examination of patient specific factors across diagnostic subgroups may be helpful in pinpointing potentially modifiable risk factors or mechanisms of action.

When viewed alongside previous work, this study highlights three important points. First, all children requiring surgical repair in the first year of life are at high risk for executive dysfunction at school age, regardless of cardiac diagnosis. Second, individual factors (such as prematurity, gender, and CHD with aortic obstruction) that potentially influence brain maturation and subsequent susceptibility to injury may be more predictive of neurodevelopmental outcomes than the broader distinction of single ventricle versus two ventricle CHD. Third, it is important to look beyond global measures like IQ in evaluating outcomes in children with CHD.

This study also suggests that many children who may qualify for services and supports in the school setting are not receiving them. Our

TABLE 4 Odds of children with CHD and clinically elevated BRIEF scores receiving special education services

Indices/subscales	*N* (%) receiving services	Odds ratio	95% CI	*P* value*
Metacognitive index				
Initiate	11 (40.7%)	1.63	0.64, 4.15	.34
Working memory	13 (35.1%)	1.18	0.49, 2.86	.82
Planning/organization	14 (41.2%)	1.80	0.73–4.39	.25
Organization of materials	9 (29%)	0.76	0.30–1.94	.64
Monitor	10 (41.7%)	1.68	0.64–4.41	.32
Behavior regulation index				
Inhibit	10 (50%)	2.55	0.92, 7.06	.10
Shift	12 (41.4%)	1.73	0.69, 4.33	.34
Emotional control	11 (40.7%)	1.63	0.64, 4.15	.34

Note: * Fisher's exact test.
BRIEF, Behavior Rating Inventory of Executive Function; CHD, congenital heart disease.

TABLE 5 Results of logistic regression models by BRIEF subscale

	Indices/*subscale*							
	Metacognitive index					Behavior regulation index		
Variable	*Initiate* OR (95% CI)	*Working memory* OR (95% CI)	*Planning/ organization* OR (95% CI)	*Organization of materials* OR (95% CI)	*Monitor* OR (95% CI)	*Inhibit* OR (95% CI)	*Shift* OR (95% CI)	*Emotional control* OR (95% CI)
Single ventricle	0.61	0.72	0.58	**0.27**	0.48	0.30	1.48	**0.28**
	(0.22, 1.71)	(0.28, 1.88)	(0.22, 1.56)	**(0.09, 0.81)**†	(0.16, 1.47)	(0.08, 1.12)	(0.54, 4.07)	**(0.08, 0.98)** †
Aortic obstruction	1.86	2.19	1.39	**4.58**	1.44	2.04	1.87	**5.95**
	(0.69, 5.07)	(0.84, 5.69)	(0.52, 3.68)	**(1.58, 13.24)** ‡	(0.48, 4.31)	(0.57, 7.32)	(0.66, 5.25)	**(1.74, 20.37)** ‡
Prematurity	**3.75**	**3.31**	2.97	2.72	2.82	**11.12**	3.11	**15.12**
	(1.20, 11.75) †	**(1.05, 10.41)** †	(0.95, 9.26)	(0.82, 9.09)	(0.85, 9.31)	**(2.62, 47.12)**‡	(0.95, 10.15)	**(3.56, 64.17)** ‡
Neurological abnormality	0.70	0.54	0.75	0.61	2.35	0.58	0.52	0.49
	(0.21, 2.30)	(0.17, 1.67)	(0.24, 2.34)	(0.18, 2.07)	(0.71, 7.76)	(0.13, 2.63)	(0.15, 1.85)	(0.12, 1.99)
Male gender	1.06	2.04	**2.88**	1.43	**4.71**	**6.74**	**3.97**	3.23
	(0.41, 2.78)	(0.81, 5.13)	**(1.11, 7.51)** †	(0.53, 3.84)	**(1.46, 15.19)** ‡	**(1.62, 28.11)** ‡	**(1.34, 11.73)**†	(0.996, 10.46)
Hosmer and Lemeshow Goodness-of-fit	0.319	0.282	0.206	0.358	0.261	0.902	0.209	0.604

Notes
[a]†Significant at $P \leq .05$.
[b]‡Significant at $P \leq .01$.
BRIEF, Behavior Rating Inventory of Executive Function.

finding that only 33% of children with CHD are receiving services is consistent with previous studies in infants and toddlers suggesting that only a small number of infants with CHD participating in a neurodevelopmental follow-up program that qualified to early intervention services were receiving therapies.[46] There was a trend toward being more likely to receive services if a child with CHD had problems related to impulsivity; this makes intuitive sense, since impulsive children can be disruptive in a classroom setting. Despite this, our data suggest that impulsivity is not one of the more commonly reported problems in this group; only 22% of children with CHD had problems in this area. In other words, the majority of children in this sample will not likely be identified for services in the school setting. Taken together, these findings suggest neurodevelopmental assessment across childhood and adolescence is needed as identification of the problem is a critical first step to ensuring appropriate access to therapies and supports, and to continue to identify those children with more subtle difficulties in school age.

There are limitations to the current study which will be addressed in future work. A primary deficiency was reliance on parent report on questionnaire for identification of concomitant neurological abnormalities. This may have resulted in under-reporting of neurological abnormalities. Furthermore, there are likely differing standards for neurologic assessment over time and in different hospitals (e.g., not all hospitals routinely provide MRI or neurological examinations for cardiac patients). As such, our classification may represent only severe neurological abnormalities such as overt stroke or seizures. In the future, precise measures of neurological maturity and injury, even in the absence of overt symptoms, will likely prove more fruitful. Additionally, data regarding key medical variables were not always consistently available. This includes use of mechanical circulatory support, or specific surgical data including duration of cardiopulmonary bypass and/or hypothermic circulatory arrest. Identification of those with a prenatal vs. postnatal diagnosis and data relating to degree of hemodynamic compromise at presentation were not available and may be useful in future studies as predictors of outcome. Careful measurement of socioeconomic status was also not readily available across the sample. Given previous research, this will likely have a large impact on outcomes and will be included in future data collection and analysis. Though the use of the BRIEF, a self-report measure, allowed a broad sample of children across the country to participate, this limited the type of data available for analysis. While there are limitations to using solely parent report data, the BRIEF has been shown to be a powerful tool in assessment of EF unique from traditional paper–pencil measures,[47] and even accounts for variance in neuroimaging findings of typically developing and patient populations.[48–50]

This study has important implications for clinical practice. The incidence of executive dysfunction in patients with CHD is very high, and may significantly impact a child's ability to succeed in multiple settings. Though neurodevelopmental follow up in children with CHD has been set as a practice guideline by the AHA,[2] there are no guidelines for specific areas that need to be assessed at particular time points in development. While

neurodevelopmental programs often prioritize patients with single ventricle CHD, or prioritize seeing very young children, there is evidence that *all* children with CHD requiring early surgical intervention require regular assessment through school age and adolescence, which can help ensure appropriate access to and continuity of services and therefore improve outcomes. This work also suggests that follow up should include a detailed evaluation of specific cognitive skills like EF. The goal of future research will be to identify which measures are the most sensitive and specific predictors of neurodevelopmental problems in children with CHD, and to work toward selection of effective screening tools (such as the BRIEF) that can be used routinely in cardiology clinics. Future research will also be directed toward evaluation of the prevalence of neurodevelopmental problems in children with decreased heart function or defects such as aortic stenosis undergoing catheter intervention, as they may share similar risk factors with respect to brain maturation. Evaluation of patient specific medical and demographic factors that may confer increased risk for executive dysfunction in later childhood will help create tiered levels of risk for assessment, and "flag" those patients in need of closer monitoring and follow up. Finally, this work suggests a need for specific interventions at school age to improve EF, especially with respect to working memory and flexibility.

With increasing survivorship, there is a strong impetus to better understand those factors that impact a child's quality of life. A better understanding of the complex medical and demographic factors that predict specific neurodevelopmental and psychosocial outcomes will help determine the mechanisms behind these outcomes. This will aid in the development of better standards of care and interventions to improve outcomes for children with CHD and their families.

AUTHOR CONTRIBUTIONS

Jacqueline Sanz contributed to the concept/design of the study, securing funding, data collection, data analysis and interpretation, drafting and revising the article.

Madison Berl contributed to the concept/design of the study, securing funding, and critical revision of the article.

Anna Chelsea Armour contributed to the concept/design of the study, data collection, data analysis, and critical revision of the article.

Yao Cheng contributed to statistical analysis and interpretation, drafting and critical revision of the article.

Jichuan Wang contributed to the design of the study, statistical analysis and interpretation, and drafting and critical revision of the article.

Mary Donofrio contributed to the concept/design of the study, securing funding, data analysis and interpretation, drafting and revising the article.

CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest with the contents of this article.

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