Neurocognitive, Academic, and Health-Related Quality of Life Outcomes in Survivors of Childhood Hemorrhagic Stroke

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A dissertation submitted to the Faculty of Graduate Studies in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Graduate Program in Psychology

York University

Toronto, Ontario

October 2025

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Abstract

Childhood stroke is a salient cause of disability in children and youth. Emerging evidence suggests that a substantial proportion of survivors of childhood hemorrhagic stroke face neurocognitive, academic, and psychosocial challenges. Despite hemorrhagic stroke accounting for half of childhood stroke cases, there are very few studies examining these outcomes in this population. My doctoral dissertation contains three clinical studies that address these gaps. Study 1 examined the neurocognitive and academic outcomes in this population. Twenty-four patients with a history of childhood hemorrhagic stroke participated in this study. Results showed lower mean scores across all neurocognitive and academic measures relative to normative means, a higher proportion of children scoring in the extremely low ranges, and more pronounced deficits in divided attention and mathematics. In terms of predictors, findings suggest a possible quadratic relationship between age at stroke and outcome and increased variability in performance was identified as hemorrhage volume increased. Study 2, a case series, described the influence of three clinical predictors: hemorrhage laterality, hemorrhage volume, and age at stroke, on neurocognitive outcomes in three patients with a history of childhood hemorrhagic stroke of similar etiology and hematoma location. Findings from Study 2 highlighted variable verbal outcomes in cases, the potential role of hemorrhage volume in neurocognitive sequelae of stroke survivors, and mild to moderate executive functioning challenges in all cases. Study 3 examined health-related quality of life (HRQoL) in survivors of childhood hemorrhagic stroke and the role of factors previously identified in the literature on five HRQoL domains: physical well-being, psychological well-being, moods and emotions, social support and peers, and school environment. Results showed that participants' parent-rated HRQoL was lower only for physical well-being. While age at stroke and socioeconomic status did not influence HRQoL. Lower FSIQ

predicted poorer HRQoL in the social support and peers domain. Lower executive functioning was associated with lower ratings in all five dimensions. Overall, the three studies provide a comprehensive understanding of neurocognitive, academic, and quality of life outcomes after childhood hemorrhagic stroke. The findings are intended to guide future research, clinical practice, and service development to support optimal recovery in this population.

Acknowledgements

This dissertation represents the culmination of my lengthy journey as a student. The years of studying and research would not have been possible without the support of many individuals.

First and foremost, I would like to express my sincere gratitude to my supervisors and mentors on my internal committee: Dr. Mary Desrocher, Dr. Robyn Westmacott, and Dr. Debra Pepler. Mary, I am forever grateful for your belief in me. From taking me as an undergrad in your lab to guiding me as your graduate student, your patience and support have profoundly impacted my journey. You stood by me during my most challenging times, reminding me of my potential when I felt hopeless. I would not have been here without your support, and I am indebted to the time and effort you have invested in my growth. Robyn, I am very fortunate to have had you on my team. Your expertise and mentorship have not only enhanced my understanding of pediatric stroke but have also inspired me to strive for excellence in my research and clinical work. You are an exceptional clinician, researcher, and mentor, and I am genuinely grateful for the impact you have had on my journey to becoming a scientist-practitioner in pediatric neuropsychology. Deb, thank you for your all your support and insights throughout my research and learning journey. Your encouragements to explore various lenses and different perspectives have significantly contributed to my research, and I appreciate the time and care you invested in this project.

Thank you to the people who have made these studies possible. Claire, you have been an integral part of my learning and have helped me grow so much as a researcher. I really appreciate all the time and effort you have put into this project. It has been so inspiring to work alongside someone as passionate and knowledgeable as you! Kaitlyn, thank you for being my partner in this project and for all your support with testing, scoring, coding, and more. Hiba, thank you for

all your positivity, encouragement, and generosity, and for helping me with testing and recruitment! Evelyn, thank you for your help with recruitment and for keeping everything very organized! Nataly, I really appreciate your statistical guidance and your support with all the analysis in this project! I also wanted to extend my gratitude to Dr. Dlamini, Dr. Désiré, Dr. Chowdhury, and Dr. Dirks; this project could not have been possible without your support, insights, and expertise in pediatric stroke. I am very thankful for the opportunity to learn from each of you! I further extend my gratitude to my clinical supervisors and mentors, Dr. Anna Gold, Dr. Trish Williams, Dr. Dahlia Fisher, and Dr. Julia Young. Although not directly involved in my dissertation, you have provided invaluable support and guidance that have significantly contributed to my growth as a scientist-practitioner throughout my doctoral journey.

I would not be here without the love and support of my family and friends. Nima, you have been my partner and rock through this seemingly endless journey; I could not have done it without you by my side. Your constant patience, encouragement, and love have kept me going. Thank you for believing in me and for all the ways you put me first. For the long nights you waited, the weekends you gave up, the vacations we never had, and everything you set aside so that I could achieve this milestone. Maman, I cannot thank you enough for all your sacrifices and love, which have carried me through every step of this journey. From the bottom of my heart, I am incredibly thankful for everything you have done for me, and I hope to honour your love throughout my life. Jaleh, you are my greatest cheerleader and biggest supporter. Your faith in me and insightful advice have kept me grounded, focused on the bigger picture, and reminded me that life is about more than just my PhD. Having you as a little sister has been a source of strength for me. I cannot thank you enough for being there through all the ups and downs. Nilgoon, thank you for always being there to listen to my complaints, for everything you have

done to cheer me up, and for all those early morning phone calls. Your support has brought so much light into my days. Yasi, thank you for all those long calls we have had. Your validation, positivity, and belief in me made all the difference when the work felt so overwhelming. Flora, we started as cohort members, but we grew into PhD buddies. You patiently listened and guided me with all the issues that came along the way. Thank you for our weekly planning sessions and your support in keeping me accountable during every step of this dissertation and our training. I cherish every moment we have shared along the way!

My sincere thanks to all the families who volunteered their time to the advancement of research. This project could not have been realized without you!

Finally, I dedicate this dissertation to two extraordinary men who have profoundly shaped my life and who I wish could be here to witness this milestone. To my Baba, who instilled in me the values of hard work, motivation, sacrifice, and perseverance, I carry your values and lessons in my heart every day. And to my Babai, who fostered my passion for learning; your wisdom and memories have been my guiding light.

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Chapter 1: Overview of Pediatric Hemorrhagic Stroke

Childhood stroke is a salient cause of disability in children and youth (Gordon, 2014), defined as a stroke occurring between the ages of 28 days and 18 years (Ferriero et al., 2019). An overview of childhood hemorrhagic stroke is essential for appreciating the rationale behind each study in this dissertation. This chapter covers the definition, prevalence, neurophysiology, etiology, and risk factors of childhood hemorrhagic stroke, as well as the mortality and sequelae and the neurocognitive and psychosocial trajectories of survivors of pediatric stroke.

Definition and Prevalence of Pediatric Stroke

Stroke is a cerebrovascular event of acute onset, resulting from a clot or a ruptured vessel that disrupts normal blood flow in the brain (Festa et al., 2008). Stroke is classified based on its pathophysiology into two categories: ischemic and hemorrhagic stroke. In ischemic stroke, the interruption of blood flow deprives the affected brain regions of oxygen and nutrients, leading to permanent brain tissue damage, called infarction (Festa et al., 2008). Hemorrhagic stroke refers to bleeding caused by ruptured cerebral vessels (Askarova & Zhurkabayeva, 2024). Pediatric stroke can occur at different developmental stages: stroke occurring between 28 weeks of gestation to 28 days after birth is categorized as a perinatal stroke, and stroke that occurs from 28 days after birth to 18 years of age is classified as a childhood stroke (Ferriero et al., 2019). Childhood stroke has an incidence of 2 to 13 per 100,000 per year, with hemorrhagic stroke accounting for the incidence of half of childhood strokes (Askarova & Zhurkabayeva, 2024; Ferriero et al., 2019).

Neurophysiology of Hemorrhagic Stroke

Non-traumatic hemorrhagic stroke (i.e., hemorrhage is not caused by a head injury) is typically characterized according to the specific location of the hemorrhage, as the

neurophysiology of hemorrhagic stroke varies depending on the location of the bleed. The three principal types of non-traumatic hemorrhagic stroke include intracerebral hemorrhage (ICH), intraventricular hemorrhage (IVH), and meningeal hemorrhage. In ICH, blood infiltrates brain tissue directly, resulting in mechanical compression, increased intracranial pressure, and neuronal injury (Keep et al., 2012). Further, the breakdown products of blood, such as hemoglobin and iron, trigger oxidative stress, inflammation, and cell death (Keep et al., 2012). IVH is characterized by bleeding in the ventricular system, often causing cerebrospinal fluid (CSF) obstruction, hydrocephalus, and damage to the periventricular white matter (Ballabh, 2013). In meningeal hemorrhage, bleeding occurs in the epidural, subdural, or subarachnoid areas between the brain and the skull, inducing cerebral vasospasm, delayed ischemia, cortical inflammation, and disrupted CSF absorption (Sanicola et al., 2023). However, despite the location of the hemorrhage, the overflowing blood following hemorrhagic stroke initiates a detrimental cascade, resulting in oxidative damage, excitotoxicity, the breakdown of the blood-brain barrier, and prolonged neuroinflammation (Westmacott & Baron, 2020).

Etiology and Risk Factors of Pediatric Hemorrhagic Stroke

Pediatric stroke arises from a range of etiologies that differ from those observed in adults, both in terms of frequency and clinical ramifications. The clinical characteristics associated with specific causes, including aneurysm morphology, as well as the nuances of these causes, such as the types of vascular malformations, differ between pediatric and adult patients (Chowdhury et al., 2022). Etiologies of pediatric hemorrhagic stroke can be categorized into cerebrovascular lesions, hematological diseases, intracerebral conditions that increase the risk of bleeding, systemic diseases or treatments that elevate bleeding risk, and rare genetic disorders (Chowdhury et al., 2022).

Cerebrovascular lesions include vascular malformations (i.e., arteriovenous malformations, aneurysms, cavernous malformations) and intracranial vascular diseases such as Moyamoya disease (i.e., a progressive condition of the intracranial arteries associated with fragile collateral vessels prone to rupture). Vascular malformations are the most common risk factor associated with non-traumatic pediatric hemorrhagic strokes and account for 48% of cases (Ferriero et al., 2019). Arteriovenous malformation (AVM) is a common vascular malformation characterized by abnormal connections and a lack of typical branching structures between the arterial and venous systems. The abnormal connections between the arteries and veins result in high-pressure blood flow, causing the vessel walls to weaken, further making them prone to rupture and increasing the risk of hemorrhage (Gulati & Kalra, 2003).

Hematological diseases such as bleeding disorders (e.g., hemophilia, von Willebrand disease, thrombocytopenia), and disseminated intravascular coagulation, leukemia (due to thrombocytopenia or coagulopathy) are also considered risk factors for pediatric hemorrhagic stroke. Bleeding disorders are primarily a risk factor for hemorrhagic stroke in the first years of life (Boulouis et al., 2019). Intracerebral conditions such as oncological lesions (e.g., brain tumours), infections, and inflammation also increase the risk of bleeding. However, in rare cases, tumours have caused hemorrhagic stroke (Boulouis et al., 2019). Systemic diseases that compromise vascular integrity or require frequent use of anticoagulation medications, such as small vessel vasculopathies or autoimmune diseases, also increase the risk of hemorrhage (Giang et al., 2018). Rare genetic disorders, including COL4A1 mutations and hereditary hemorrhagic telangiectasia, may also predispose children to hemorrhage (Boulouis et al., 2019).

Looking specifically at childhood nontraumatic hemorrhagic stroke, etiologies can be categorized into structural and hematologic causes, and about 10% of childhood hemorrhagic

strokes are idiopathic (Ferriero et al., 2019). Structural causes account for 75% of childhood hemorrhagic stroke cases and include AVMs, aneurysms, arteriovenous fistulas, cavernous malformations, and spontaneous hemorrhage into brain tumours, with AVMs being the most common cause (Ferriero et al., 2019). Hematologic causes can be divided into inherited and acquired. Within the inherited causes, bleeding disorders such as Hemophilia A, Hemophilia B, and von Willebrand disease account for approximately 90% of hematologic cases, and rare clotting factor deficiencies (e.g., factors II, VII, XIII, and vitamin K-dependent deficiencies) account for 3–5% of hematologic cases. Idiopathic thrombocytopenic purpura is considered the most common acquired hematologic disorder (Ferriero et al., 2019).

Mortality and Sequelae of Hemorrhagic Stroke

Overall pediatric stroke is among the top ten causes of death in children (Greenham et al., 2016). Ischemic strokes are more common in adults, whereas in neonates and children, hemorrhagic and ischemic strokes occur with comparable incidence (Riel-Romero et al., 2009). Pediatric hemorrhagic stroke, compared to ischemic stroke, is associated with higher early neurological deterioration, need for intensive care, and acute morbidity (Malone et al., 2022).

It is important to note that most literature on mortality and morbidity of pediatric hemorrhagic stroke focuses specifically on ICH (Malone et al., 2022), though ICH accounts for only half of pediatric hemorrhagic strokes (Jordan & Hillis, 2007). Pediatric ICH is associated with significant mortality and long-term disability. Mortality rates for perinatal ICH range from 12% to 25% (Brouwer et al., 2010; Porcari et al., 2020). In childhood ICH, these rates can vary more substantially, ranging from 4% to 33% (Beslow et al., 2010; Beslow et al., 2014; Fox et al., 2012; Lo et al., 2013). It is noteworthy that the largest population-based study identified a mortality rate of 4% in childhood hemorrhagic stroke. However, it also highlighted that 73%

required admission to intensive care units (Fox et al., 2012). Multiple factors have been explored in terms of predictors of mortality following pediatric hemorrhagic stroke. Key predictors of mortality in childhood ICH stroke include older age at presentation, coagulopathy, and coma (Ferriero et al., 2019).

Despite the lower mortality rates in some larger studies, compared to perinatal ICH, childhood ICH often results in substantial functional impairments, with over one-third of survivors experiencing significant long-term neurological disability (Porcari et al., 2018). Pediatric stroke is an important cause of childhood disability (Ferriero et al., 2019). Most survivors suffer long-term neurological deficits that can include various cognitive, motor, sensory, and visual impairments (Beslow et al., 2010; Blom et al., 2003; deVeber et al., 2000; Greenham et al., 2016; Lynch & Han, 2005; Mercuri et al., 2001; Roach et al., 2008). Motor challenges, epilepsy, and cognitive challenges are among the most common long-term neurological consequences following pediatric hemorrhagic stroke (Ferriero et al., 2019).

Motor outcomes vary depending on the age at onset and severity of the hemorrhage, with perinatal ICH survivors having better outcomes compared to childhood ICH survivors. A hospital-based cohort study reported that full-term infants with perinatal ICH were at an 8.6% increased risk of developing cerebral palsy (Brouwer et al., 2010). In contrast, motor impairments are reported to be more frequent in childhood ICH, with 38% to 60% of survivors reporting some level of motor impairments (Blom et al., 2003; Broderick et al., 1993; Greenham et al., 2016; Yvon et al., 2018). Further, survivors of childhood ICH, are at increased risk of epilepsy. A prospective cohort study showed 4% of children developed epilepsy within one-year post-ICH, with this increasing to 13% by two years (Beslow et al., 2010).

Cognitive and educational challenges are also commonly found in long-term follow-up studies (Blom et al., 2003; Hawks et al., 2016; Yvon et al., 2018). Although outcomes are not consistently and clearly defined in the literature, several factors have been associated with poorer neuropsychological outcomes. These include greater ICH volume, altered mental status within 6 hours of presentation, an infratentorial location of the hemorrhage, a lower Glasgow Coma Scale score upon admission, an aneurysmal cause of the hemorrhage, being under the age of 3 at the time of ICH, and having underlying hematological disorders (Ferriero et al., 2019).

Neurocognitive Trajectory

Childhood hemorrhagic stroke is less studied in the pediatric stroke literature relative to childhood ischemic stroke, as traditionally, hemorrhagic stroke has been viewed as less likely to result in severe neurological or neuropsychological impairments in children (Lo et al., 2008). However, recent studies highlight the "growing into deficit" concept, suggesting that childhood stroke survivors may encounter additional physical and cognitive challenges as they develop, leading to emerging deficits and rehabilitation needs, a concept that has been included in the Canadian stroke best practice recommendations (Hebert et al., 2016). These findings indicate that childhood survivors of hemorrhagic stroke, even in the absence of early post-stroke neurocognitive impairments, may be at risk of neurocognitive challenges during later stages of their development. A longitudinal follow-up study revealed that 17 out of 31 survivors exhibited cognitive impairment 10 years post-childhood hemorrhagic stroke, with 10 showing mild and 7 showing moderate to severe impairments (Blom et al., 2003). Academic and educational challenges have also been reported long term, with approximately 50% of school-aged survivors of ICH requiring educational support one-year post-stroke (Hawks et al., 2016), and 40% being enrolled in special education programs at a median of 43 months follow-up (Yvon et al., 2018).

Moreover, existing literature on the broader pediatric stroke suggests that neurocognitive deficits (Bolk et al., 2022; Bosenbark et al., 2018; Jacomb et al., 2018; Champigny et al., 2024; L. K. Murphy et al., 2017; Peterson et al., 2019; Rivella & Viterbori, 2021; Westmacott et al., 2010, 2018; Janas et al., 2023) and academic challenges (Champigny et al., 2020; Deotto et al., 2019; Peterson et al., 2019; Yvon et al., 2018) commonly occur following these injuries.

The existing literature on the neurocognitive outcomes in the childhood hemorrhagic stroke population suggests that survivors generally fall within the clinically average (L. K. Murphy et al., 2017; Wingeier et al., 2011) to low average ranges (Champigny et al., 2025; Yvon et al., 2018) on measures of intelligence, with some studies suggesting domain-specific deficits such as working memory and processing speed (L. K. Murphy et al., 2017). However, the current literature has limited generalizability, with many studies combining samples of children with hemorrhagic and ischemic stroke or relying on overall neurological functioning or global measures of intelligence as their primary cognitive outcome following childhood hemorrhagic stroke (de Montferrand et al., 2019; Lo et al., 2013).

While there are limited studies exploring academic outcomes in childhood hemorrhagic stroke population, previous literature suggests that neurocognitive deficits hinder academic advancement in the pediatric stroke (Champigny et al., 2020; Hawks et al., 2016; Li et al., 2022; Peterson et al., 2019; Yvon et al., 2018) and the broader pediatric brain injury (Fluss & Lidzba, 2020; Vanderlind et al., 2022) populations. Academic difficulties have been observed in children with ischemic stroke, with particular weaknesses in math calculation and reading comprehension (Peterson et al., 2019). Childhood ischemic stroke survivors are more likely to require extra help at school, accommodations, individual education plans, and assistive technology (Champigny et al., 2020).

In spite of the established findings that deficits commonly occur following pediatric stroke, the neurocognitive sequelae in this patient population remain partially understood. This lack of a comprehensive understanding is primarily attributable to the complexities inherent in injuries affecting the developing brain. The ongoing maturation and myelination of the cortical areas is one of the complicating factors in understanding the neurocognitive sequelae of pediatric stroke (Funahashi, 2022). Disruptions in the development of specific brain regions can not only impact that specific region but also the connected areas, as well as other regions that mature over time (Anderson et al., 2002; Herman et al., 2002), suggesting that injuries to specific brain regions can have extensive impacts on other regions. Additionally, pediatric strokes are complex and can vary not only in terms of the pathophysiology and developmental stage during which they occur, but also with respect to the location and severity of the injury. Furthermore, lesions can cross boundaries between cortical and subcortical areas, making it challenging to study a specific subgroup (Durston & Casey, 2006).

Psychosocial Trajectory

It is well established that the majority of survivors of pediatric stroke experience lifelong residual neurological, motor, or functional impairments (Cnossen et al., 2010; Gordon, 2014; Greenham et al., 2016). Beyond these visible sequelae, studies report that survivors of pediatric stroke may be at heightened risk of behavioural, emotional, and psychosocial difficulties. More specifically, pediatric stroke can cause significant problems in emotional and behavioural functioning, communication, interpersonal relationships, and social interactions (Champigny, et al., 2024; Gomes et al., 2014; Gordon, 2014; Greenham et al., 2017). Further, as discussed above, the emerging and evolving neurological, motor, or functional impairments can disrupt academic progress, social participation, and emotional well-being, ultimately leading to a lower

health-related quality of life (HRQoL) (Gordon, 2014). Despite the importance of HRQoL, a recognized gap exists in research addressing how childhood stroke affects participation, peer relationships, and emotional regulation (Gomes et al., 2014; Gordon, 2014; Greenham et al., 2017).

The literature on HRQoL in pediatric stroke is sparse and mixed. While some studies report lower overall HRQoL, or only specific challenges in domains of physical, school, and social functioning (Cnossen et al., 2010; Fong et al., 2025; Friefeld et al., 2011; Ghotra et al., 2018; Lo et al., 2013; Neuner et al., 2011; O'Keeffe et al., 2012), others indicate that HRQoL remains intact (Caspar-Teuscher et al., 2019; Darteyre et al., 2014; Rohner et al., 2020; Simma et al., 2007). Further, most studies have focused on ischemic stroke or looked at a combined sample of ischemic and hemorrhagic stroke.

Conclusion

Despite the awareness of the longer-term neurocognitive, academic, and quality of life implications following childhood hemorrhagic stroke, research in this domain remains limited. Previous studies have primarily explored neurological functioning following pediatric hemorrhagic stroke (Jordan et al., 2009; Kleinman et al., 2012; Liu et al., 2015), and investigations into the neurocognitive and psychosocial outcomes for this population remain limited. Those focusing on neurocognitive outcomes have utilized global measures of intelligence as the primary outcome domain (Blom et al., 2003; L. K. Murphy et al., 2017; Wingeier et al., 2011; Yvon et al., 2018). My doctoral dissertation includes three clinical studies aiming to remedy these shortcomings in the scientific literature and enhance the clinical outcomes for childhood survivors of hemorrhagic stroke and their families. Study 1 examines the neurocognitive and academic outcomes, alongside identifying predictors of these outcomes.

Study 2, a case series, offers an in-depth exploration of the neurocognitive profiles of three cases with similar etiology and hemorrhage location, aiming to discuss and elucidate the predictors of neurocognitive sequelae in this population. Study 3 investigates the quality of life and its predictors in this population.

Chapter 2: Aims and Hypotheses

Study 1

The overarching goal of this study was to characterize the neurocognitive and academic outcomes and examine the impact of potential predictors of intellectual and academic outcomes in survivors of childhood hemorrhagic stroke. Predictors included age at stroke, hemorrhage volume, hemorrhage laterality, and socioeconomic status (i.e., household income and maternal education). The neurocognitive outcomes assessed included verbal comprehension, perceptual reasoning, working memory, processing speed, full-scale IQ, measures of attention (i.e., sustained visual attention, sustained auditory attention, and divided attention) and performance-based executive functioning (i.e., cognitive flexibility). From these neurocognitive domains, verbal comprehension, perceptual reasoning, working memory, processing speed, and full-scale IQ were considered as measures of intellectual outcomes. The academic outcomes assessed included single-word reading, mathematical calculation, and single-word spelling.

Aim 1.

Our first aim was to characterize the neurocognitive outcomes of survivors of childhood hemorrhagic stroke. Neurocognitive challenges in the childhood ischemic stroke population are well documented, and a significant percentage of the childhood stroke group is expected to fall within the borderline or impaired levels on these measures (Jacomb et al., 2018). In contrast, studies investigating neurocognitive outcomes following childhood hemorrhagic stroke are sparse. A review of the literature suggests that youth with a history of hemorrhagic stroke generally skew toward the clinically average (Blom et al., 2003; L. K. Murphy et al., 2017; Wingeier et al., 2011) to low average ranges (Yvon et al., 2018) on measures of intelligence, with some studies suggesting domain-specific deficits such as working memory and processing

speed (L. K. Murphy et al., 2017). However, previous literature on the neurocognitive outcomes of childhood survivors of hemorrhagic stroke has limited generalizability due to assessing this population with comorbid perinatal conditions (i.e., preterm birth, extremely low birthweight) or within samples combining hemorrhagic and ischemic stroke (de Montferrand et al., 2019).

In accordance with the literature, we hypothesized that the neurocognitive outcomes of childhood survivors of hemorrhagic stroke would differ from the norms on the mean scores of the neurocognitive domains assessed. Given the mixed findings in the literature, no hypothesis was put forward regarding the severity of neurocognitive deficits.

Aim 2.

Our second aim was to characterize the academic outcomes of survivors of childhood hemorrhagic stroke. Previous literature suggests that neurocognitive deficits hinder academic advancement (Champigny et al., 2020; Hawks et al., 2016; Li et al., 2022; Peterson et al., 2019; Yvon et al., 2018) in the pediatric stroke population and broader pediatric brain injury population (Fluss & Lidzba, 2020; Vanderlind et al., 2022). However, studies exploring academic outcomes specifically following childhood hemorrhagic stroke are sparse. In accordance with the literature, we hypothesized that (1) the academic outcomes of pediatric survivors of hemorrhagic stroke would differ from the norms on the mean scores of the measures of mathematical calculations, reading, and spelling. Given the mixed findings in the literature, no hypothesis was put forward regarding the impact of the severity of deficits on these academic domains.

Aim 3.

Our third aim was to investigate the impact of age at injury on the intellectual and academic outcomes in the childhood hemorrhagic stroke population. There is considerable evidence that neurocognitive and academic outcomes vary according to age in the pediatric brain injury

population. Early childhood injury has been associated with more pronounced challenges in executive function, memory, and attention (Babikian & Asarnow, 2009; Goh et al., 2021) and long-term academic performance, especially reading skills (Haarbauer-Krupa et al., 2019) and middle childhood injury associated with worse intellectual outcomes (Crowe et al., 2012). The pediatric stroke literature remains fragmented, with mixed findings that support either the plasticity hypothesis (Max et al., 2010) or the vulnerability hypothesis (Everts et al., 2008; Jacomb et al., 2018; Max et al., 2010; Peterson et al., 2019; Westmacott et al., 2010). Some studies suggest a non-linear relationship, where recovery might follow an inverted U-shaped curve (Allman & and Scott, 2013; Everts et al., 2008), while others propose a U-shaped curve, dependent on the specific cognitive functions affected (Abgottspon et al., 2022) and academic areas of reading, math, and spelling (Sullivan et al., 2022). Studies of childhood hemorrhagic stroke population specifically, have suggested favourable neurocognitive outcomes for youth sustaining stroke in later childhood or adolescence (Everts et al., 2008; Jacomb et al., 2018; Max et al., 2010; Peterson et al., 2019; Westmacott et al., 2010).

In accordance with the literature, we hypothesized that there would be a polynomial quadratic relationship between age at stroke and intellectual outcomes in childhood survivors of hemorrhagic stroke. Given the mixed findings in the literature, no hypothesis was put forward regarding the concavity of the polynomial relationship (i.e., a U shape or a reverse U shape). Further, given the lack of research into academic outcomes following childhood hemorrhagic stroke, no hypothesis was put forward regarding the association between age at the time of stroke and academic outcome.

Aim 4.

We aimed to explore the impact of hemorrhage volume on *the* intellectual and academic outcomes in the childhood hemorrhagic stroke population.

Based on previous research on childhood survivors of ischemic stroke (Abgottspon et al., 2022; Bartha-Doering et al., 2021; Bosenbark et al., 2017; Long et al., 2011; Westmacott et al., 2010) and the pediatric brain injury population (Bourke et al., 2022; Ferrazzano et al., 2024), we hypothesized that those with smaller hemorrhage volumes would have higher scores on measures of intellectual outcome compared to those with medium and large hemorrhage volumes. Given the association between the cognitive and academic outcomes following childhood hemorrhagic stroke, we hypothesized that those with smaller hemorrhage volumes would have higher scores on measures of academic outcome compared to those with medium and large hemorrhage volumes.

Aim 5.

We aimed to explore the impact of hemorrhage laterality on the intellectual and academic outcomes in the childhood hemorrhagic stroke population. Studies exploring the neurocognitive outcomes and hematoma laterality in the pediatric stroke population are mixed. While some suggest no significant effect of the injury hemisphere (Abgottspon et al., 2022; Avila et al., 2010; Bosenbark et al., 2017; Champigny et al., 2024; Everts et al., 2008; Jacomb et al., 2018; Long et al., 2011; O'Keeffe et al., 2014; Peterson et al., 2019), others report notable challenges with verbal comprehension, receptive language, verbal memory, working memory, and knowledge of vocabulary (Allman & and Scott, 2013; de Montferrand et al., 2019; Funnell & Pitchford, 2010; Lidzba et al., 2017), following a left hemisphere injury. Academic skills are highly complex and require interconnections between different lobes, and the neural networks underlying academic

skills of mathematical calculations and literacy are widely distributed and may involve both hemispheres (Arsalidou & Taylor, 2011; Matejko & Ansari, 2015; Menon, 2014; Rapcsak & Beeson, 2015), making it challenging to determine the trajectory of academic outcomes based on solely right vs left hemisphere injury.

In accordance with the literature, we hypothesized that (1) the intellectual outcomes of childhood survivors of hemorrhagic stroke would not differ between those sustaining stroke in the left hemisphere versus the right hemisphere, with the exception of language-related outcomes, (2) as such we hypothesized that those with hemorrhagic stroke impacting the left hemisphere would show more deficits in language-related intellectual abilities (i.e., verbal comprehension) compared to those with right hemisphere hemorrhage. Given the lack of research into the impact of hematoma laterality and academic outcomes following pediatric hemorrhagic stroke and the complexity and interconnection between lobes for academic skills of math and literacy, no hypothesis was put forward regarding academic areas of deficit based on hemorrhage laterality.

Aim 6.

We aimed to explore associations between socioeconomic status and the intellectual and academic outcomes following childhood hemorrhagic stroke. Socioeconomic status has been associated with cognitive and academic outcomes in various normative (Fernald et al., 2013; Lurie et al., 2021; Noble et al., 2007) and brain injury populations (Cohen-Zimerman et al., 2019; Venturini et al., 2024). Socioeconomic status has also been identified as a predictor in a study combining youth with ischemic and hemorrhagic stroke (Champigny et al., 2024) and two studies on pediatric ischemic stroke (Bartha-Doering et al., 2021; Peterson et al., 2019). However, to date, no published studies have examined the impact of socioeconomic status on

intellectual and academic outcomes in survivors of childhood hemorrhagic stroke. Given previous research, we hypothesized that lower socioeconomic status, as measured by maternal education and household income, would negatively influence the intellectua*l* and academic outcomes in our sample.

Study 2

The overarching goal of this study was to characterize and discuss the influence of three clinical predictors of hemorrhage laterality, hemorrhage volume, and age at stroke on the neurocognitive outcomes of three patients (one female age 13, two males ages 15 and 17), with history of childhood hemorrhagic stroke with similar etiology (i.e., arteriovenous malformation) and hematoma location (i.e., broadly within the left temporoparietal region). The neurocognitive outcomes assessed included verbal comprehension, perceptual reasoning, working memory, processing speed, verbal fluency, expressive and receptive language, aspects of executive function (i.e., inhibition switching and set shifting), and learning and memory.

Aim 1.

Our first aim was to describe the neurocognitive outcomes of the three survivors of childhood hemorrhagic stroke who had a similar etiology (i.e., arteriovenous malformation) and hematoma location (i.e., left broadly within the temporoparietal region). We aimed to describe and identify patterns of similarity and difference in neurocognitive profiles among the three cases, providing insight into the neurocognitive sequelae of childhood survivors of hemorrhagic stroke. This is an exploratory aim, and as such, no hypothesis was put forward.

Aim 2.

Our second aim was to explore the impact of left hemisphere hemorrhage on the neurocognitive outcomes of the three survivors of childhood hemorrhagic stroke who had a similar etiology and similar hematoma location (i.e., broadly within the left temporoparietal region). Studies on neurocognitive outcomes and laterality in children are mixed. While some suggest no significant effect of the injury side (Everts et al., 2008; Ganesan, 2013), others report notable challenges with receptive language, verbal memory, working memory, and knowledge of vocabulary (Allman & and Scott, 2013; Blom et al., 2003; Funnell & Pitchford, 2010; Rowan et al., 2007), following a left hemisphere injury.

Given the exploratory nature of this review, no a priori hypotheses were put forward; however, in accordance with the literature, we expected to observe patterns that may suggest that the three cases who had sustained stroke in the left hemisphere will show challenges in one or more language-related neurocognitive domains (e.g., verbal comprehension, verbal fluency, expressive and receptive language, and verbal learning and memory).

Aim 3.

We aimed to explore the impact of hemorrhage volume on the neurocognitive outcomes of the three survivors of childhood hemorrhagic stroke who had a similar etiology and similar hematoma location (i.e., broadly within the left temporoparietal region). Given the exploratory nature of this review, no a priori hypotheses were put forward, however, based on the literature on childhood survivors of ischemic stroke (Abgottspon et al., 2022; Bartha-Doering et al., 2021; Long et al., 2011; Westmacott et al., 2018) and the pediatric brain injury population (Bourke et al., 2022; Ferrazzano et al., 2024), we expected that the case with smaller hemorrhage volume

would have higher scores on measures of neurocognitive outcome compared to the two cases with medium hemorrhage volumes.

Aim 4.

We aimed to explore the impact of age at injury on the neurocognitive outcomes of the three survivors of childhood hemorrhagic stroke who had a similar etiology and similar hematoma location (i.e., broadly within the left temporoparietal region). Given the exploratory nature of this review, no a priori hypotheses were put forward, however, per previous studies on childhood hemorrhagic stroke population suggesting favourable neurocognitive outcomes for youth sustaining stroke in later childhood or adolescence (Everts et al., 2008; Jacomb et al., 2018; Max et al., 2010; Peterson et al., 2019; Westmacott et al., 2010), we expected to observe patterns that may suggest that the two cases who sustained stroke in adolescence would have higher scores on measures of neurocognitive outcome compared to the case who sustained stroke in early childhood.

Study 3

The overarching goal of this study was to characterize the health-related quality of life (HRQoL) and examine the impact of potential predictors of this outcome in survivors of childhood hemorrhagic stroke. Predictors included age at stroke, socioeconomic status (i.e., household income), full-scale IQ, and parent-rated global executive functioning composite. The HRQoL domains assessed included physical well-being, psychological well-being, moods and emotions, social support and peers, and school environment.

Aim 1.

Our first aim was to characterize the HRQoL outcomes of survivors of childhood hemorrhagic stroke. HRQoL challenges in childhood ischemic stroke and broader pediatric brain injury population are well documented (Cnossen et al., 2010; Fong et al., 2025; Friefeld et al., 2011; Ghotra et al., 2018; Gorgoraptis et al., 2019; Lo et al., 2013; Neuner et al., 2011; O'Keeffe et al., 2012). In contrast, studies investigating this outcome following childhood hemorrhagic stroke are sparse. A review of the literature suggests mixed findings, while some have found that youth with a history of stroke generally have intact HRQoL (Darteyre et al., 2014; Rohner et al., 2020; Simma et al., 2007), others suggest domain-specific deficits such as physical, psychological, school, and social functioning challenges (Cnossen et al., 2010; Fong et al., 2025; Friefeld et al., 2011; Ghotra et al., 2018; Lo et al., 2013; Neuner et al., 2011; O'Keeffe et al., 2012).

In accordance with literature, we hypothesize that (1) the parent-rated HRQoL outcomes of childhood survivors of hemorrhagic stroke would differ from the norms on one or more of the domains assessed and (2) given the mixed findings in the literature, no hypothesis was put forward regarding the extent and severity of challenges in the five domains of HRQoL measured.

Aim 2.

Our second aim was to investigate the impact of clinical and demographic predictors: age at stroke, socioeconomic status, intellectual abilities, and executive functioning abilities on HRQoL of childhood hemorrhagic stroke survivors. There is considerable evidence that functional outcomes vary based on clinical and demographic factors. Factors such as age, socioeconomic status, and cognitive abilities have been associated with HRQoL in pediatric stroke populations; however, these associations are mixed and limited (Cnossen et al., 2010;

Friefeld et al., 2011; Ghotra et al., 2015; Neuner et al., 2011; Simma et al., 2007), and data on childhood survivors of hemorrhagic stroke are lacking. Given the mixed findings of the previous studies and limited literature, no hypothesis was put forward regarding the linear relationship between these predictors and the five domains of HRQoL.

Chapter 3: Neurocognitive and Academic Outcomes Following Childhood Hemorrhagic Stroke: Patterns and Predictors

Publication Status and Author Contributions

The following chapter is based on a manuscript which, as of October 2025, has been submitted for publication in *Journal of Child Neurology* and is awaiting a decision from the editorial office. Currently, the reference for this manuscript is as follows:

Kahnami, L., Champigny, C. M., Beribisky, N.,Desrocher, M., Butterfield, K. M., Désiré, N., Dlamini, N., Chowdhury, S.S., Dirks, P., & Westmacott, R. (2025). Neurocognitive and Academic Outcomes Following Childhood Hemorrhagic Stroke: Patterns and Predictors. [Manuscript submitted for publication]. Department of Psychology, York University.

Leila Kahnami, the first author, spearheaded the research efforts, which included conceptualizing the study, applying for approval from the Research Ethics Boards at the Hospital for Sick Children and York University, recruiting participants, collecting data, analyzing and interpreting the results, and writing the manuscript for publication.

Abstract

There is limited understanding of neurocognitive and academic sequelae following pediatric hemorrhagic stroke, and the predictors of outcomes. This study examined neurocognitive and academic outcomes in youth (n=24, ages 5-18) with hemorrhagic stroke in childhood. Our results demonstrated a) lower mean scores across all neurocognitive and academic measures relative to normative means, b) a higher proportion of children scoring in the extremely low ranges, and c) more pronounced deficits in divided attention and mathematics. Further, this study examined the impact of four predictors (age at stroke, hemorrhage volume and laterality, and socioeconomic status) on intellectual and academic outcomes. Findings suggest a possible quadratic relationship between age at stroke and outcome. Increased variability in performance was identified as hemorrhage volume increased. No differences were found based on laterality. Socioeconomic status was positively associated with verbal comprehension and mathematical calculations. Clinical implications include the importance of timely and regular neuropsychological follow-up and advocating for educational resources to address the resource disparity and inequity for survivors of childhood hemorrhagic stroke.

Introduction

Childhood stroke is an important cause of acquired brain injury in children and youth (Fuentes et al., 2016), defined as a stroke occurring between the ages of 28 days and 18 years (Ferriero et al., 2019). The majority of survivors experience long-term neurological and neurocognitive difficulties (Beslow et al., 2010; Chowdhury et al., 2022). Hemorrhagic strokes account for almost 50% of childhood strokes and refers to bleeding in the brain parenchyma or surrounding areas caused by ruptured cerebral blood vessels (Askarova & Zhurkabayeva, 2024). Childhood hemorrhagic stroke has been associated with a higher initial mortality rate but a lower likelihood of experiencing severe neurological or neuropsychological impairments (Lo et al., 2008). This type of stroke has received less attention in pediatric research than ischemic stroke (Ferriero et al., 2019), despite the knowledge that neurocognitive deficits commonly occur (Bolk et al., 2022; Bosenbark et al., 2018; Champigny et al., 2024, 2025; Jacomb et al., 2018; Janas et al., 2023; Kahnami et al., 2025; L. K. Murphy et al., 2017; Peterson et al., 2019; Rivella & Viterbori, 2021; Westmacott et al., 2010, 2018). Academic deficits are also common in this population (Yvon et al., 2018). This gap in research results in a limited understanding of the neurocognitive and academic trajectories in this population.

The literature on the neurocognitive profile of survivors of childhood hemorrhagic stroke suggests that these youth generally skew toward the clinically average (Champigny et al., 2025; L. K. Murphy et al., 2017; Wingeier et al., 2011) to low average ranges (Yvon et al., 2018) on measures of intelligence. Some studies suggest domain-specific deficits in areas of working memory and processing speed (L. K. Murphy et al., 2017), and a higher likelihood of deficits in processing speed and verbal learning/memory (Champigny et al., 2025). However, the current literature has limited generalizability due to using samples combining hemorrhagic and ischemic

stroke and using global intellectual scores as the main measure of outcome (de Montferrand et al., 2019; Lo et al., 2013). Neurocognitive deficits have been associated with lower academic advancement in pediatric stroke (Champigny et al., 2020; Hawks et al., 2016; Li et al., 2022; Peterson et al., 2019; Yvon et al., 2018) and pediatric brain injury (Fluss & Lidzba, 2020; Vanderlind et al., 2022). Neurocognitive deficits can hinder academic achievement by causing difficulties with learning core skills such as literacy and mathematics as well as disrupting day-to-day functioning (e.g., sustaining attention in class, following instructions). Over a third of youth with hemorrhagic stroke have been shown to require special education (Yvon et al., 2018), yet studies exploring academic outcomes are sparse.

There is considerable evidence that neurocognitive and academic outcomes vary based on age at injury in pediatric populations. The pediatric stroke literature remains fragmented, with mixed findings that support older age at injury is associated with worse outcomes (Abgottspon et al., 2022; Max et al., 2010; O'Keeffe et al., 2014) or the opposite, that younger age at injury is associated with worse outcomes (Everts et al., 2008; Jacomb et al., 2018; Max et al., 2010; Peterson et al., 2019; Westmacott et al., 2010). Other researchers have documented a non-linear relationship, where recovery might follow an inverted U-shaped curve (Allman & and Scott, 2013; Everts et al., 2008) or a U-shaped curve dependent on the specific cognitive functions affected (Abgottspon et al., 2022).

There is substantial evidence that a larger bleed volume is associated with more pronounced neurocognitive and academic challenges (Abgottspon et al., 2022; Bartha-Doering et al., 2021; Bosenbark et al., 2017; Bourke et al., 2022; Champigny et al., 2024; Long et al., 2010; Westmacott et al., 2010) regardless of location of injury (Ferrazzano et al., 2024).

Laterality of hemorrhage may also affect neurocognitive outcomes, though findings in the pediatric stroke population are mixed. While some studies suggest no significant effect based on the injury hemisphere (Abgottspon et al., 2022; Avila et al., 2010; Bosenbark et al., 2017; Champigny et al., 2024; Everts et al., 2008; Jacomb et al., 2018; Long et al., 2010; O'Keeffe et al., 2014; Peterson et al., 2019), others report notable challenges with receptive language, verbal memory, working memory, and vocabulary following injury in the left hemisphere (Allman & and Scott, 2013; de Montferrand et al., 2019; Funnell & Pitchford, 2010; Lidzba et al., 2017; Rowan et al., 2007).

Socioeconomic status (SES) has been associated with cognitive and academic outcomes in typically developing (Fernald et al., 2013; Lurie et al., 2021; Noble et al., 2007) and brain injury populations (Cohen-Zimerman et al., 2019; Venturini et al., 2024). SES has been identified as a predictor in a study of ischemic and hemorrhagic stroke (Champigny et al., 2024) and two studies on ischemic stroke (Bartha-Doering et al., 2021; Peterson et al., 2019).

The primary aim of this study was to characterize the neurocognitive and academic outcomes in survivors of childhood hemorrhagic stroke. The secondary aim was to determine whether clinical and demographic predictors – age at stroke, hemorrhage volume, hemorrhage laterality, and SES – predict the intellectual and academic outcomes in this population.

Materials and Methods

Participants

The hospital's neurovascular program's database was used to identify childhood hemorrhagic stroke patients with a hematoma documented on magnetic resonance imaging or computed tomography. Inclusion criteria consisted of a history of a non-traumatic hemorrhagic stroke occurring between the ages of 28 days and 18 years, 5 to 18 years of age at the time of

participation, at least six months post-stroke at the time of participation, and proficiency in English. Exclusion criteria included unstable medical condition and inability to complete neuropsychology measures (e.g., due to severe intellectual disability). To ensure a representative sample of the diverse pediatric stroke population, participants were not excluded based on medical or psychiatric comorbidities or stroke etiology. 64 families were invited to participate between September 2023 and July 2024, and 24 agreed to the study.

Ethical Considerations

The study was approved by the Research Ethics Board of Hospital for Sick Children in Toronto, Canada. Researchers explained the study goals and procedures to youth and their caregivers as part of the informed consent procedure. Written caregiver consent and participant assent or consent were gathered from participating families.

Procedures

Participants completed a series of neuropsychological and tests as described below, while caregivers completed the demographic questionnaire. Measures were administered, scored, and interpreted by clinical pediatric neuropsychologists or senior Ph.D. students in clinical pediatric neuropsychology.

Demographic Characteristics

Demographic information was collected through a background questionnaire completed by caregivers. Interpreter services were used to assist parents who were not proficient in English. The following demographic variables were included: native language, language(s) spoken at home, maternal education level, and household income. Maternal education and household

income were selected to represent SES. These SES variables were treated as continuous variables in analyses.

Clinical Characteristics

Age at Stroke, Age at Testing, and Time Since Stroke

Age at stroke, age at neuropsychological testing, and time since stroke were measured as continuous variables. Age at stroke was calculated based on the date of clinical presentation, age at testing was based on the date of the testing, and time since stroke was the difference between age at stroke and age at testing.

Hemorrhage Characteristics

Participants' medical chart, neurology reports, and neuroimaging reports were reviewed to obtain hemorrhage characteristics. Hemorrhage type was classified based on the primary anatomical site of the bleed. Hemorrhage laterality, anatomical region, lobe location, structural involvements, and etiology were coded. Hemorrhage size was coded according to Beslow's Pediatric Intracerebral Hemorrhage Score (Beslow et al., 2014). Hemorrhage volume and total brain volume were calculated via the ABC/XYZ method. The hematoma was classified as small (≤ 2% of TBV), medium (> 2-3.99% of TBV), or large (≥ 4% of TBV) (Beslow et al., 2014), by a pediatric neuropsychologist. For the subdural (n=1) and subarachnoid (n=1) bleeds, hemorrhage volume was not estimated due to the limitations in applying volumetric techniques to extra-axial bleeds. Surgical procedures were coded as well based on type of procedure.

Neurocognitive and Academic Measures

Neurocognitive outcomes were quantified using scores on standardized neuropsychological tests assessing verbal comprehension, perceptual reasoning, working

memory, processing speed, full-scale IQ, cognitive flexibility, sustained visual attention, sustained auditory attention, and divided attention. The specific subtests are described in Table 1. The academic outcomes were quantified using scores on standardized academic tests assessing word reading, mathematical calculations, and spelling. Scores were determined relative to age-based normative data on intellectual and academic abilities (M=100, SD=15), and attention and executive functioning (M=10, SD=3).

Statistical Analysis

All analyses were performed using R (v4.2.1), with statistical significance set at $p < .05$ with corresponding 95% confidence intervals (CIs). Descriptive statistics were used to describe the clinical and demographic characteristics of the hemorrhagic sample. The mean standard and scaled scores on neurocognitive and academic variables were calculated. Patterns in results on neurocognitive and academic outcomes are qualitatively described following the classification system of the American Academy of Clinical Neuropsychology(Guilmette et al., 2020). The proportion of children scoring within the extremely low range (i.e., 2 standard deviations below the mean, standard score <70 or scaled score <4) for each variable was calculated.

Neurocognitive variables were examined to ensure that parametric assumptions were met. Shapiro-Wilk test and Q-Q plots informed the normality of data distribution. A series of one-sample *t*-tests was conducted to compare the scores of the sample across intellectual, academic, attention, and executive functioning measures, with the norms. Benjamini-Hochberg False Discovery Rate correction (Benjamini & Hochberg, 1995) was used to control for inflation of Type I error due to multiple comparisons, and adjusted *p*-values ($p_{adjusted}$) were used to determine statistical significance. Cohen's d effect sizes were calculated to quantify the size of the

difference between the childhood hemorrhagic stroke sample and normative mean (Cohen, 1988).

To address our secondary objective, exploratory analyses were conducted to investigate potential relationships between intellectual and academic outcome measures and neurologic (hemorrhage laterality, hemorrhage size) and demographic variables (age at stroke, maternal education, and household income). Given the small sample size and the aim to determine the impact of multiple predictors, we focused on identifying patterns and trends for those predictors with more than one coefficient (i.e., age at stroke as a quadratic relationship was assumed, and hemorrhage volume as it was categorized into 3 different sizes). Significance testing was not conducted to examine factors including age at stroke and hemorrhage volume given the small sample size and consequent risk of increased Type II error. Instead, descriptive comparisons were used, with locally estimated scatterplot smoothing (LOESS) for age at stroke and boxplots for hemorrhage volume. The following significance testing results are included in the supplementary material: a series of spline regressions which were conducted to examine the non-linear relationship between age at stroke and intellectual and academic outcomes in line with previous study examining this association (Champigny et al., 2024) and a series of univariate linear regressions which were conducted to examine the impact of hemorrhage volume on each intellectual and academic variable. These results are presented in the supplementary material (Supplementary Tables 1 and 2). A series of Welch's *t*-tests examined differences across groups based on hemorrhage laterality. For this analysis, one participant with a bilateral hemorrhage was excluded. Levene's test of equality of variances assessed homogeneity of variance across groups. A series of univariate linear regressions investigated relationships between the intellectual and academic outcomes, and household income and maternal education. The overall model fit (*F*-

statistic, *p*-value, and R^2) and individual parameter estimates (unstandardized beta coefficients, standard errors, and *p*-values) are provided for each linear regression.

Results

Demographic and Clinical Characteristics

Twenty-four children (50% female) participated in the study. The mean age at testing was 12.02 (*SD*= 3.76). All participants were fluent in English, and English was the primary language spoken at home for the majority of participants (75.0%). Most participants were right-handed (87.50%). In terms of educational level at testing, most participants were in elementary school (45.83%).

In terms of the socioeconomic variables, over half of parents had a college or undergraduate level education (58.33% of mothers and 54.16% of fathers). About half of families (54.16%) reported a household income above $100,000. A summary of the demographic characteristics is presented in Table 2.

In terms of participants' clinical characteristics, the mean age at stroke onset was 7.98 years (*SD* = 4.63) with most strokes (58.33%) occurring in late childhood (6–18 years). Intracerebral hemorrhage was the primary area of hemorrhage in twenty-two participants, one had a subdural hemorrhage, and one had a subarachnoid hemorrhage. The most common etiology of hemorrhage was an AVM malformation (*n*=15). Other etiologies included cavernous malformation (*n*=2), cortical vein thrombosis (*n*=1), and unknown or unconfirmed etiology (*n*=6). A summary of clinical characteristics is presented in Table 3.

Table 1

The Neurocognitive and Academic Variables and Associated Measures in Study 1

Neurocognitive outcome	Standardized measure
Intellectual indices	
Verbal comprehension	Verbal Comprehension Index (subtests: Similarities and Vocabulary) of the Wechsler Intelligence Scale for Children, 5th Edition (Wechsler, 2014)/ Verbal Comprehension Index (subtests: Similarities, Vocabulary, and Information) of the Wechsler Adult Intelligence Scale, 4th Edition (Wechsler, 2008)/ Verbal Comprehension Index (subtests: Similarities and Vocabulary) of the Verbal Comprehension Index (subtests: Similarities and Vocabulary) of the Wechsler Pre-School and Primary Scales of Intelligence, 4th Edition (Wechsler, 2012)
Perceptual reasoning	The mean of Visual Spatial (subtests: Block Design and Visual Puzzles) and Fluid Reasoning Indices (subtests: Matrix Reasoning and Figure Weights) of the Wechsler Intelligence Scale for Children, 5th Edition (Wechsler, 2014)/ Perceptual Reasoning Index (subtests: Block Design, Visual Puzzles, and Matrix Reasoning) of the Wechsler Adult Intelligence Scale, 4th Edition (Wechsler, 2008)/The mean of Visual Spatial (subtests: Block Design and Object Assembly) and Fluid Reasoning Indices (subtests: Matrix Reasoning and Picture Concepts) of the Wechsler Pre-School and Primary Scales of Intelligence, 4th Edition (Wechsler, 2012)
Working memory	Working Memory Index (subtests: Digit Span and Picture Span) of the Wechsler Intelligence Scale for Children, 5th Edition (Wechsler, 2014)/ Working Memory Index (subtests: Digit Span and Arithmetic) of the Wechsler Adult Intelligence Scale, 4th Edition (Wechsler, 2008) / Working Memory Index (subtests: Picture Memory and Zoo Locations**)** of the Wechsler Pre-School and Primary Scales of Intelligence, 4th Edition (Wechsler, 2012)
Processing speed	Processing Speed Index (subtests: Coding and Symbol Search) of the Wechsler Intelligence Scale for Children, 5th Edition (Wechsler, 2014)/ Processing Speed Index (subtests: Coding and Symbol Search) of the Wechsler Adult Intelligence Scale, 4th Edition (Wechsler, 2008) / Processing Speed Index (subtests: Bug Search and Cancellation) of the Wechsler Pre-School and Primary Scales of Intelligence, 4th Edition (Wechsler, 2012)
Full scale IQ	FSIQ Index (subtests: Similarities, Vocabulary, Block Design, Matrix Reasoning, Figure Weights, Digit Span, Coding) of the Wechsler Intelligence Scale for Children, 5th Edition (Wechsler, 2014)/ FSIQ Index (subtests: Similarities, Vocabulary, Block Design, Matrix Reasoning, Digit Span, Arithmetic, Symbol Search, Coding) of the Wechsler Adult Intelligence Scale, 4th Edition (Wechsler, 2008) /FSIQ Index (subtests: Information, Similarities, Block Design, Matrix Reasoning, Picture Memory, Bug Search) of the Wechsler Pre-School and Primary Scales of Intelligence, 4th Edition (Wechsler, 2012)
Other neurocognitive domains	
Cognitive flexibility	Set Shifting: Trail Making Switching score of the Trail Making Test of the Delis-Kaplan Executive Function Systems (Delis et al., 2001)
Sustained visual attention	Attention score of the Sky Search subtest of Test of Everyday Attention for Children(Manly et al., 1998)/ Detectability (d′) score of the Conners Continuous Performance Test, Third Edition (Conners, 2014)
Sustained auditory attention	The Score! subtest of Test of Everyday Attention for Children (Manly et al., 1998)
Divided attention	The Sky Search DT subtest of Test of Everyday Attention for Children (Manly et al., 1998)
Academic outcome	Standardized measure
Word reading	The Word Reading subtest of Wechsler Individual Achievement Test-Third Edition (Wechsler, 2009)
Mathematical calculation	The Numerical Operations subtest of Wechsler Individual Achievement Test-Third Edition (Wechsler, 2009)
Spelling	The Spelling subtest of Wechsler Individual Achievement Test-Third Edition (Wechsler, 2009)

Table 2

Demographic Characteristics of the Hemorrhagic Stroke Sample in Study 1

Sex *n (%)*	
Female	12 (50.0%)
Male	12 (50.0%)
Gender *n (%)*	
Female	11 (45.83%)
Male	12 (50.0%)
Non-Binary	1 (4.17%)
Native language *n (%)*	
English	18 (75.0%)
Other	6 (25.0%)
Number of languages spoken at home *n (%)*	
English only	10 (41.67%)
English and 1 other language	10 (41.67%)
English and 2 other languages	4 (16.67%)
Age at assessment (years) *M* (*SD*)	12.02 (3.76)
Educational level at assessment *n (%)*	
Elementary school (Kindergarten to Grade 6)	11 (45.83%)
Middle school (Grades 7 and 8)	8 (33.33%)
High school (Grades 9 to 12)	5 (20.83%)
Handedness *n (%)*	
Right	21 (87.50%)
Left	3 (12.50%)
Maternal education	
Did not finish high school	1 (4.17%)
High school degree	6 (25.0%)
College degree	8 (33.33%)
University undergraduate degree	6 (25.0%)
Postgraduate degree	3 (12.50%)
Family income	
$25,000 - $49,999	3 (12.50%)
$50,000 - $74,999	4 (16.67%)
$75,000 - $99,999	4 (16.67%)
$100,000 - $149,999	4 (16.67%)
Over $150,000	9 (37.50%)

Table 3

Clinical Characteristics of the Hemorrhagic Stroke Sample in Study 1

Age at stroke (years) *M* (*SD*)	7.98 (4.63)
Stroke onset age group *n (%)*	
Early childhood (28 days-5 years)	10 (46.67%)
Late childhood (6-18 years)	14 (58.33%)
Time since stroke (years) *M* (*SD*)	4.03 (3.34)
Type of hemorrhagic stroke *n (%)*	
Intracerebral hemorrhage (ICH)	22 (91.67%)
Subdural hemorrhage (SDH)	1 (4.17%)
Subarachnoid hemorrhage (SAH)	1 (4.17%)
Hemorrhage cause *n (%)*	
AVM (vascular malformations)	15 (62.50%)
Cavernous (vascular valformations)	2 (8.33%)
Cortical vein thrombosis (CVST)- venous abnormalities	1 (4.17%)
Idiopathic	6 (25.0%)
Hemorrhage location *n (%)*	
Laterality	
Left hemisphere	12 (50.0%)
Right hemisphere	11 (45.83%)
Bilateral	1 (4.17%)
Region	
Supratentorial	13 (54.16%)
Infratentorial	5 (20.83%)
Intraventricular	3 (12.50%)
Combined (supra- and infratentorial)	2 (8.33%)
Structures	
Cortical	16 (66.67%)
Subcortical	3 (12.50%)
Combined cortical-subcortical	1 (4.17%)
Brainstem	1 (4.17%)
Cerebellar	3 (12.50%)
Hemorrhage size *n (%)*	
Small	9 (37.50%)
Medium	9 (37.50%)
Large	4 (16.67 %)
N/A	2 (8.33%)
Surgery *n (%)*	
No surgical procedure	8 (33.33%)
AVM resection (including craniotomy)	10 (41.67%)

Embolization	2 (8.33%)
External ventricular drain placement (EVD)	2 (8.33%)
EVD and AVM resection	2 (8.33%)

Neurocognitive and Academic Outcomes

T-test results, described in Table 4 revealed that the hemorrhagic participants performed significantly lower than the normative mean on general intellectual indices of verbal comprehension (mean difference -12.33, $p = .006$), working memory (mean difference -12.92, $p = .003$), processing speed (mean difference -10.33, $p = .024$), and full-scale IQ (mean difference -11.41, $p = .007$). Cognitive flexibility (mean difference -2.62, $p = .013$), sustained visual attention (mean difference -2.62, $p = .009$), and divided attention (mean difference -4.53, $p < .001$) were also significantly lower compared to the normative mean. On standardized measures of academic ability, children with hemorrhagic stroke performed significantly lower than the normative mean across domains of single-word reading (mean difference -9.43, $p = .045$), mathematical calculation (mean difference -16.74, $p < .001$), and single-word spelling (mean difference -8.96, $p = .034$). Although our sample had significantly lower scores on these measures, the mean differences between our sample and the normative population surpassed one standard deviation only on the measures of divided attention and mathematical calculation. There were no significant differences between the hemorrhagic stroke group and the normative data on measures of perceptual reasoning and sustained auditory attention. A higher proportion of participants (4-26%) scored in the Extremely Low range on all measures of neurocognitive and academic abilities than expected in the normative population (2%).

Table 4

The Neurocognitive and Academic Outcomes: Mean Scores and One-Sample t-test results comparing the childhood hemorrhagic stroke sample with the normative means in Study 1

Neurocognitive outcome	*M* (*SD*)	95% *CI*	*t*	df	*p*	Cohen's *d*	Extremely low *n* (%)
Verbal comprehension	87.67 (17.33)	80.35 - 94.99	-3.49	23	**.006**	-0.71	3 (12.50%)
Perceptual reasoning	95.56 (17.40)	89.03- 102.09	-1.41	23	.17	-0.29	1 (4.17%)
Working memory	87.08 (16.38)	80.17 -94.00	-3.86	23	**.003**	-0.79	3 (12.50%)
Processing speed	89.67 (19.50)	81.43- 97.90	-2.60	23	**.024**	-0.53	3 (12.50%)
Full scale IQ	88.58 (16.85)	81.47 - 95.70	-3.32	23	**.007**	-0.68	2 (8.33%)
Cognitive flexibility*	7.38 (4.04)	5.54 - 9.22	-2.97	20	**.013**	-0.65	4 (19.05%)
Sustained visual attention*	7.38 (3.72)	5.69 - 9.07	-3.23	20	**.009**	-0.70	4 (19.05%)
Sustained auditory attention*	8.26 (3.53)	6.56 - 9.96	-2.15	18	.05	-0.49	2 (10.53%)
Divided attention*	5.47 (3.29)	3.89 - 7.06	-6.00	18	**<.001**	-1.38	5 (26.32%)
Academic outcome							
Word reading	90.57 (20.47)	81.71-99.42	-2.21	22	**.045**	-0.46	3 (13.04%)
Mathematical calculation	83.26 (16.32)	76.20- 90.32	-4.92	22	**<.001**	-1.03	2 (8.70%)
Spelling	91.04 (18.35)	83.29-98.79	-2.39	23	**.034**	-0.49	5 (20.83%)

Note. Bold indicates statistical significance at $p < .05$.; all scores are standard scores ($M = 100$, $SD = 15$), except for neurocognitive domains marked by*, which are reported as mean scaled scores ($M = 10$, $SD = 3$); df = degrees of freedom; *p*-value reported after application of Benjamini-Hochberg False Discovery Rate correction; extremely low is defined as a standard score less than 70 or scaled score less than 4.

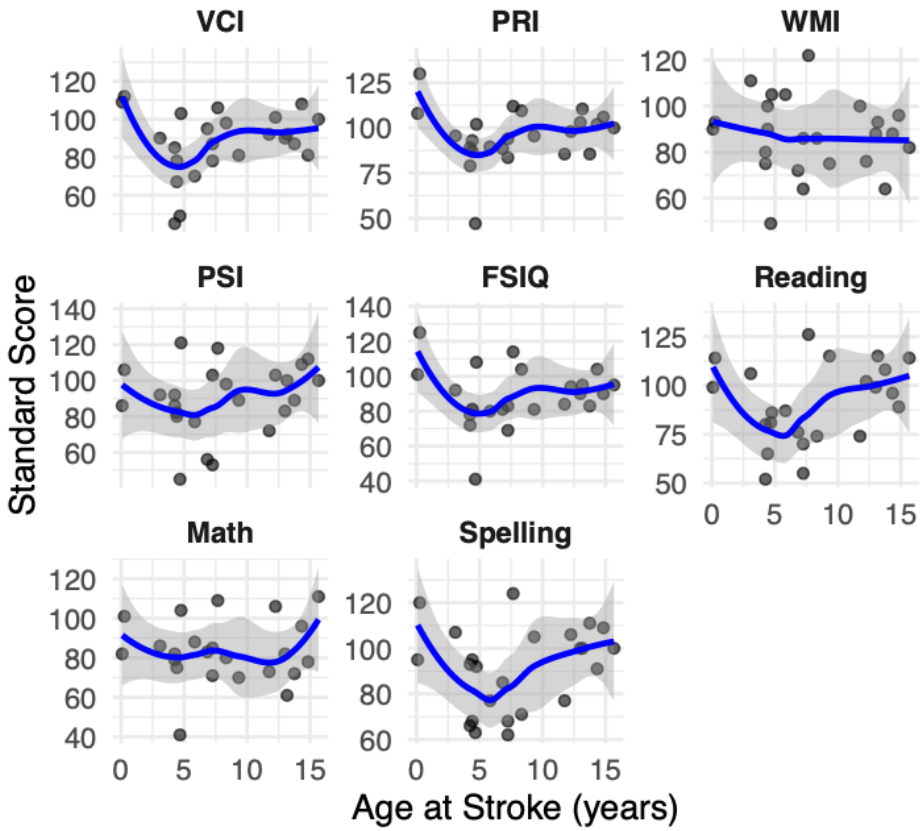
Predictors of Intellectual and Academic Outcomes

As can be seen in Figure 1, the LOESS-smoothed scatterplot showed evidence of U-shaped patterns between age at stroke and general intellectual indices of verbal comprehension, perceptual reasoning, processing speed, full-scale IQ, and academic measures of reading, mathematics, and spelling. The fitted trend lines for verbal comprehension, perceptual reasoning, processing speed, reading, and spelling illustrate scores reaching steep dips when stroke occurred around age 5, with performance generally stabilizing from approximately age 10 onward. The lowest scores on the academic measure of mathematics appear later, at around 12 years of age at

stroke, with a sharp rise onward. There was no visual evidence of a departure from linearity on the working memory line of best fit with no inflection points, suggesting a linear relationship with a mild decline from early childhood onward. For verbal comprehension, perceptual reasoning, full-scale IQ, reading, and spelling, confidence intervals were relatively narrow until age 7, and suggest more variability after age 7. Confidence intervals for working memory, processing speed, and mathematical abilities suggest more variability across all ages.

Figure 1

LOESS-Smoothed Scatterplots of Intellectual and Academic outcome as Function of Age at Stroke in Study 1

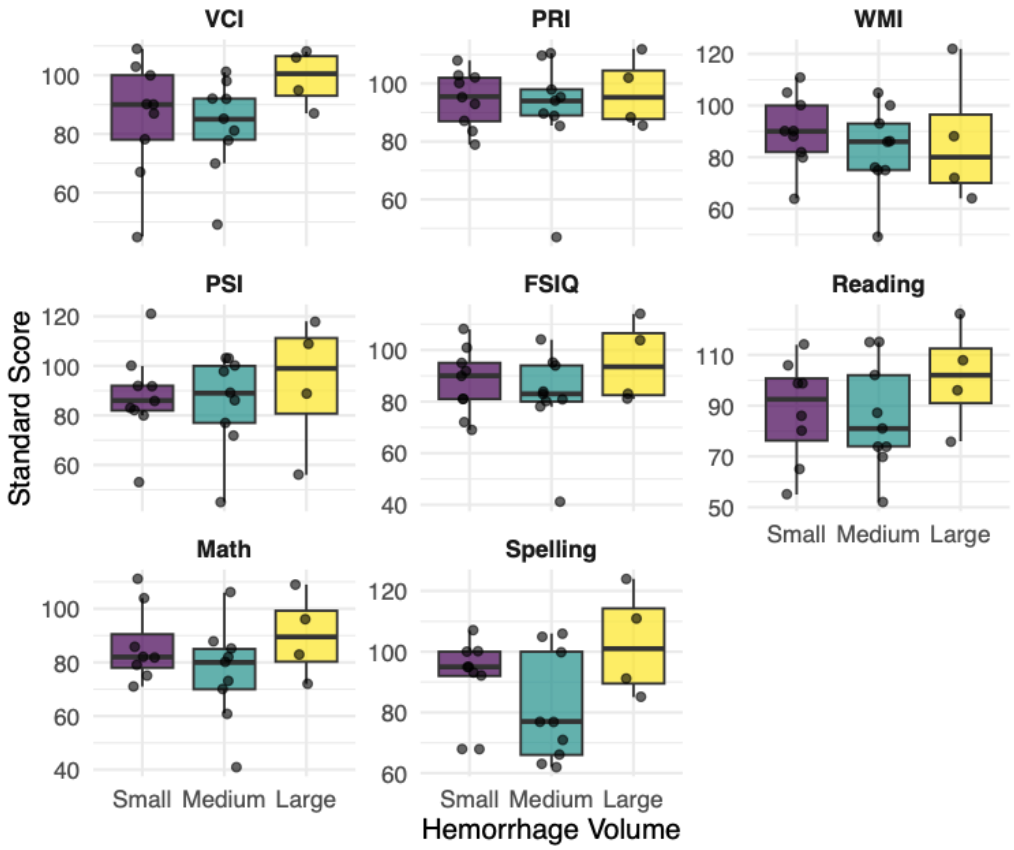


Note. X-axis represents age at stroke (in years); 95% confidence interval in gray; VCI = Verbal comprehension; PRI = Perceptual reasoning; WMI = Working memory; PSI = Processing speed; FSIQ = Full scale IQ.

Figure 2 displays the distribution of general indices of intellectual functioning and academic abilities across hemorrhage volume groups of small (*n*=9), medium (*n*=9), and large (*n*=4). The distribution of the large volume group suggests higher performance in all domains except for working memory. One participant in the large volume group showed significantly higher performance and may be considered an outlier, and as an outlier they likely contributed to the unusually high mean scores in this group. Overall, this group had fewer observations, which limited the interpretability of the data distribution. Despite this, we decided to retain this participant in the analysis due to the small sample size. The sample showed relatively comparable medians and distribution across small and medium volume groups on indices of verbal comprehension, perceptual reasoning, working memory, processing speed, and full-scale IQ. The medium-volume group showed greater variability, lower medians, and skewness toward lower standard scores compared to the small group across all academic measures of reading, mathematics, and spelling. This difference was especially evident in spelling, where the small group's performance was tightly clustered around the mean.

Figure 2

Boxplots of Intellectual and Academic Outcome by Hemorrhage Volume in Study 1



Note. VCI = Verbal comprehension; PRI = Perceptual reasoning; WMI = Working memory; PSI = Processing speed; FSIQ = Full scale IQ.

There was no evidence of significant differences on intellectual indices and academic abilities based on hemorrhage laterality. The results are described in Table 5. Figure 3 illustrates comparable performance across measures of verbal comprehension, perceptual reasoning, and working memory. Participants with right hemisphere hemorrhage displayed a lower median score on processing speed and full-scale IQ, but their scores were more tightly clustered. In contrast, the group with left hemisphere hemorrhage exhibited greater variability and included more low outliers. Participants with left hemisphere hemorrhage show a lower median on all academic

measures. This difference was mostly pronounced in their spelling performance, with wider variability and more cluster around the lower end.

Table 5

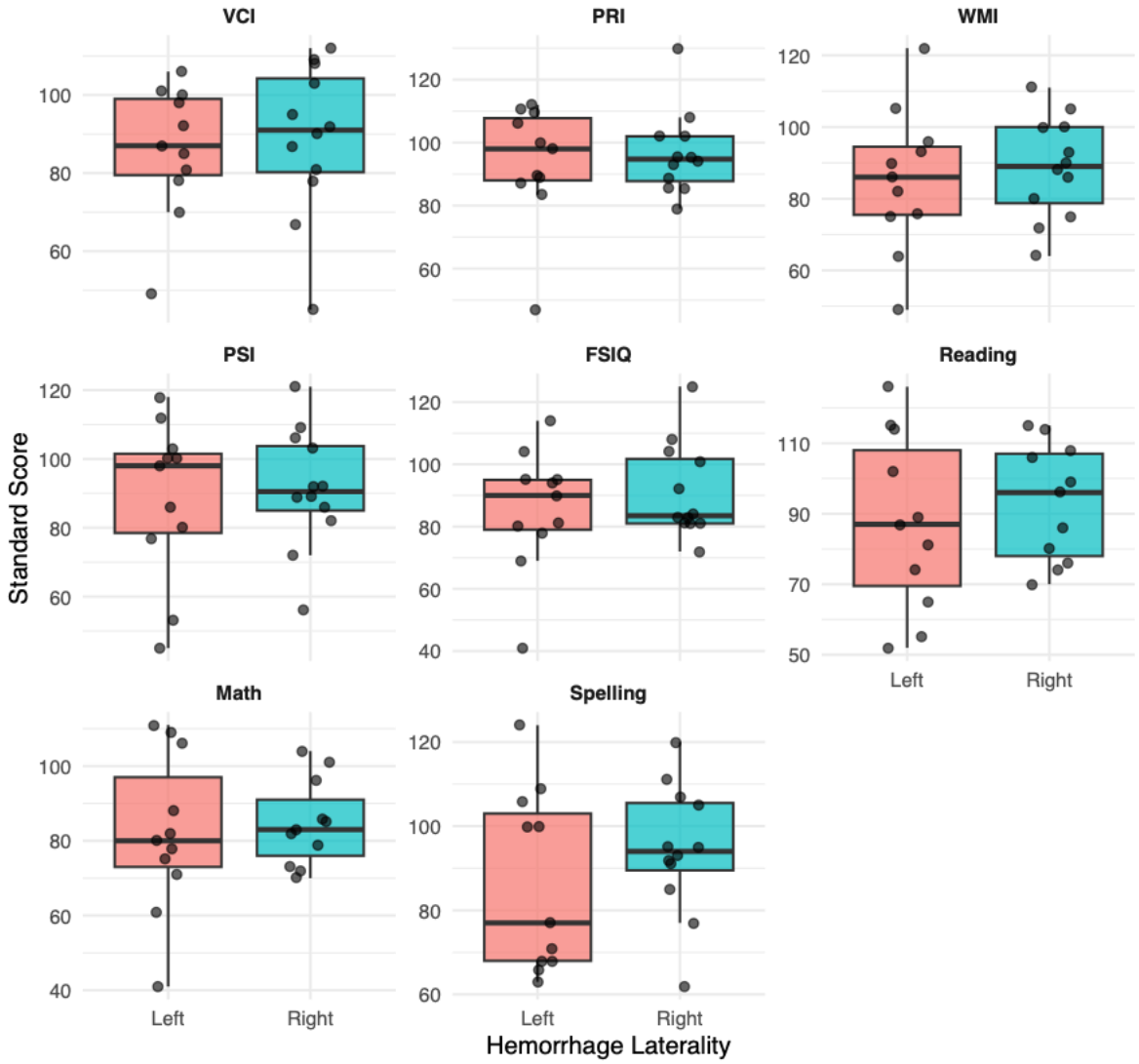
Results of Welch's t-Tests Examining Impact of Hemorrhage Laterality (Left vs Right Hemisphere) on Intellectual and Academic outcomes in Study 1

Outcome	*t*	df	*p*	*M* left hemisphere (standard score)	*M* right hemisphere (standard score)	Cohen's *d*
Intellectual outcome						
Verbal Comprehension	-0.38	20.89	0.71	86.09	88.92	-0.16
Perceptual Reasoning	-0.40	18.01	0.69	93.82	96.54	-0.17
Working Memory	-0.47	17.98	0.64	85.27	88.67	-0.20
Processing Speed	-0.36	18.47	0.73	88.36	91.42	-0.15
Full Scale IQ	-0.78	18.95	0.45	85.55	91.25	-0.33
Academic outcome						
Word Reading	-0.64	17.43	0.53	87.27	93.09	-0.27
Mathematical Calculation	-0.36	15.42	0.72	82.00	84.64	-0.15
Spelling	-1.00	18.09	0.33	86.55	94.42	-0.42

Note. df = degrees of freedom.

Figure 3

Boxplots of Intellectual and Academic Outcome by Hemorrhage Laterality (Left vs. Right) in Study 1



Note. VCI = Verbal comprehension; PRI = Perceptual reasoning; WMI = Working memory; PSI = Processing speed; FSIQ = Full scale IQ.

The univariate regression analyses presented in Tables 6 and 7, revealed that household income positively predicted scores on verbal comprehension ($p < .05$) and maternal education

positively predicted scores on mathematics ($p < .05$). These SES factors were not significantly associated with any other outcome measures.

Table 6

Results of Simple Linear Regressions Examining Impact of Household Income on Intellectual and Academic Outcomes in Study 1

Outcome	Estimate	Std. Error	*F*	df	*p*	Multiple R^2
Intellectual outcome						
Verbal comprehension	5.48	2.22	6.11	1, 22	**.022**	0.22
Perceptual reasoning	2.11	2.19	0.93	1, 22	.35	0.04
Working memory	-2.04	2.33	0.77	1, 22	.39	0.03
Processing speed	1.72	2.80	0.38	1, 22	.54	0.02
Full scale IQ	3.38	2.33	2.11	1, 22	.16	0.09
Academic outcome						
Word reading	-1.84	3.15	0.34	1, 21	.57	0.02
Mathematical calculation	3.87	2.39	2.63	1, 21	.12	0.11
Spelling	-.85	2.65	0.10	1, 22	.75	0.01

Note. Bold indicates statistical significance at $p < .05$; df = degrees of freedom.

Table 7

Results of Simple Linear Regressions Examining Impact of Maternal Education on Intellectual and Academic Outcomes in Study 1

Outcome	Estimate	Std. Error	*F*	df	*p*	Multiple R^2
Intellectual outcome						
Verbal comprehension	1.66	3.37	0.24	1, 22	.63	0.01
Perceptual reasoning	2.22	2.99	0.55	1, 22	.46	0.03
Working memory	-0.20	3.20	0.00	1, 22	.95	0.00
Processing speed	3.82	3.73	1.05	1, 22	.32	0.05
Full scale IQ	3.39	3.22	1.11	1, 22	.30	0.05
Academic outcome						
Word reading	-2.06	3.99	0.27	1, 21	.61	0.01
Mathematical calculation	6.33	2.88	4.83	1, 21	**.039**	0.19
Spelling	1.17	3.58	0.11	1, 22	.75	0.01

Note. Bold indicates statistical significance at $p < .05$; df = degrees of freedom.

Supplementary Table 1

Model Fit for Spline Regression Examining Impact of Age at Stroke on Intellectual and Academic Outcomes in Study 1

Outcome	Multiple R^2	df	F	p
Intellectual outcome				
Verbal comprehension	0.40	3, 19	4.22	.019
Perceptual reasoning	0.36	3, 19	3.52	.035
Working memory	0.02	3, 19	0.13	.94
Processing speed	0.15	3, 19	1.08	.38
Full scale IQ	0.31	3, 19	2.82	.066
Academic outcome				
Word reading	0.32	3, 18	2.78	.071
Mathematical calculation	0.05	3, 18	0.33	.81
Spelling	0.30	3, 19	2.66	.078

Note. Significant results are not bolded, results should be interpreted with caution due to the small sample size; df= degrees of freedom.

Supplementary Table 2

Results of Simple Linear Regressions Examining Impact of Hemorrhage Volume on Intellectual and Academic outcomes

Outcome	Predictor	Estimate	Std. Error	Predictor *p*	*F*	df	Model *p*	Multiple R^2
Intellectual outcome								
Verbal comprehension	Medium	-1.56	7.91	.85	2.25	2, 20	.13	0.18
	Large	17.16	9.36	.08				
Perceptual reasoning	Medium	-3.94	7.39	.60	1.05	2, 20	.37	0.10
	Large	8.71	8.75	.33				
Working memory	Medium	-8.11	8.08	.33	0.51	2, 20	.61	0.05
	Large	-3.09	9.56	.75				
Processing speed	Medium	-5.00	9.65	.61	0.38	2, 20	.69	0.04
	Large	4.71	11.42	.68				
Full scale IQ	Medium	-5.44	7.70	.49	2.24	2, 20	.13	0.18
	Large	13.73	9.11	.15				
Academic outcome								
Word reading	Medium	-1.19	9.91	.91	1.49	2, 19	.25	0.14
	Large	17.25	11.63	.15				
Mathematical calculation	Medium	-9.53	7.85	.24	1.71	2, 19	.21	0.15
	Large	6.45	9.21	.49				
Spelling	Medium	-11.11	7.86	.17	3.77	2, 20	**.04**	0.27
	Large	14.31	9.30	.14				

Note. Bold indicates statistical significance at $p < .05$; df = degrees of freedom.

Discussion

Results of the current study indicate that participants with hemorrhagic stroke had lower mean scores on all neurocognitive and academic measures compared to the normative population. Importantly, findings also identified a higher proportion of children scoring in the extremely low range on these measures than expected in the general population, with pronounced deficits in divided attention and mathematics. Our exploratory findings illustrate emerging trends related to predictors of intellectual and academic outcomes, including a possible quadratic relationship between age at stroke and outcome, increased working memory challenges as children age, and a trend toward more variable performance as hemorrhage volume increases from small to medium. Finally, our findings highlight the importance of SES factors, with household income being associated with verbal comprehension and maternal education being associated with mathematical calculations.

Neurocognitive and Academic Outcomes

Our sample of childhood survivors of hemorrhagic stroke had lower mean scores compared to norms on measures of verbal comprehension and overall intelligence, with relatively preserved visual-perceptual abilities. This is in line with the literature on traumatic brain injury; a systematic review indicated consistent findings of long-term impairment in verbal IQ in this population (Cermak et al., 2022). However, these findings contrast with studies that reported overall average verbal and intellectual abilities after hemorrhagic stroke (Blom et al., 2003; Champigny et al., 2025; L. K. Murphy et al., 2017; Wingeier et al., 2011; Yvon et al., 2018). Consistent with previous findings across studies of pediatric stroke (Hajek et al., 2013; Jacomb et al., 2018; Lansing et al., 2004; L. K. Murphy et al., 2017; O'Keeffe et al., 2014), more

white matter-based skills such as working memory, processing speed, cognitive flexibility, sustained visual attention, and divided attention were lower in our sample than the population norms.

Our findings further suggest that academic abilities are lower in this population compared to norms on measures of reading, mathematics, and spelling. This is in line with previous studies exploring academic outcomes after pediatric ischemic stroke (Champigny et al., 2020; Deotto et al., 2019; Li et al., 2022; Peterson et al., 2019) and studies that primarily explored academic outcomes through educational placement, educational level, and the level of accommodations in a pediatric hemorrhagic stroke population (Boulouis et al., 2019; Hawks et al., 2016; Yvon et al., 2018). Based on qualitative research, youth with stroke have expressed feeling overwhelmed and slower than their peers in academic contexts, which they attributed primarily to acquired neurocognitive deficits (Champigny et al., 2024). Further, challenges in divided attention and mathematics were particularly pronounced in our sample. These may be due to the complex cognitive demands these tasks impose, requiring the simultaneous engagement of working memory, attention shifting, and information processing speed – functions which may be highly vulnerable to disruption following early neurological insult (Anderson et al., 2001; Ballantyne et al., 2007).

Predictors of Intellectual and Academic Outcomes

Exploratory plotting revealed a non-linear U-shaped pattern between age at stroke and all intellectual indices with the exception of working memory. This pattern was most visible for verbal comprehension and perceptual reasoning, where the lowest scores emerged for children whose stroke occurred around 5 years of age. A greater variability in outcomes was observed when stroke occurred after age 7, suggesting that individual differences and the influence of

other factors supporting recovery trajectories may widen over time. These observed patterns align with one study suggesting a U-shaped association between age at stroke and cognitive outcomes (Abgottspon et al., 2022).

A similar pattern was noted for the academic skills of single word reading, spelling, and mathematical calculation, with overall greater variability across ages and with the lowest scores emerging at later than 5 years of age at stroke. These trends highlight that the cognitive and academic vulnerabilities may differ across domains and factors beyond the age at stroke, such as time since stroke, hemorrhage characteristics, and environmental factors (Fuentes et al., 2016; Peterson et al., 2019; Sullivan et al., 2022). This may be particularly relevant for developing academic abilities during mid childhood, a crucial period for acquiring essential academic knowledge and for the development of fundamental neural circuits that support these skills (Dennis et al., 2014). A crucial period for developing foundational early literacy skills—such as phonological awareness, oral language, and print knowledge—occurs between the ages of 3 and 6 (Kelly et al., 2023). As such, neurological injuries during this time may significantly disrupt later reading and spelling abilities. Further, the greater variability observed in academic skills compared to indices of intellectual ability across ages suggests a more heterogeneous impact of age at a stroke and the interplay of other predictors. For example, a previous study found that children with TBI who showed reduced microstructural integrity of the superior longitudinal fasciculus (Johnson et al., 2015) also demonstrated lower word-reading ability, suggesting that acquired reading deficits may be influenced not only by age at injury but also by the specific location of brain injury.

Another visible observation is that the line of best fit for age at stroke and working memory supports a negative linear relationship, with a slight decline in this ability as the age at

stroke increases. This pattern aligned with other studies that found that later strokes were often associated with more diffuse working memory and executive functioning impairments (Max et al., 2010; O'Keeffe et al., 2014). This observed pattern may be attributed to the later developmental emergence of working memory and executive functioning abilities (Funahashi, 2022; Miyake & Friedman, 2012) and may also suggest the "growing into deficit" hypothesis (Westmacott et al., 2010), which posits that challenges become more apparent as environmental and academic demands increase, revealing underlying working memory deficits over time and at later stages of childhood.

The small and medium hemorrhage participants demonstrated a relatively comparable distribution on indices of intellectual abilities, contrasting the notion that a larger injury is associated with worse neurocognitive outcomes in stroke (Abgottspon et al., 2022; Bartha-Doering et al., 2021; Bourke et al., 2022; Champigny et al., 2024; Ferrazzano et al., 2024). In line with previous research (Deotto et al., 2019), however, the medium hemorrhage group demonstrated a lower median and showed greater variability and a skewness toward lower scores compared to the small group on measures of academic abilities. This trend may indicate that among children with medium hematomas, stroke-related factors such as age at injury, individual differences in response to brain injury, and patterns of reorganization, may influence outcomes. Further, academic skills are generally more complex than intellectual skills and require integration of multiple brain regions and coordination of various cognitive skills (Geary, 2007). Future studies in this area will require larger participant samples in order to statistically control for these important brain injury variables through inferential techniques.

Hemorrhage laterality generally did not significantly predict intellectual and academic outcomes. These findings contribute to the mixed literature regarding the importance of laterality

as a predictor. Even on measures of verbal skills, which have tended to be associated with lesion laterality, youth in our sample performed similarly across groups. It is likely that the younger brain is less functionally specialized and has better potential for reorganization, which explains why laterality may not play a significant role in this population (Everts et al., 2008; Smitherman et al., 2015). Further, the neural networks underlying academic abilities are widely distributed and may involve both hemispheres (Arsalidou & Taylor, 2011; Matejko & Ansari, 2015; Menon, 2014; Rapcsak & Beeson, 2015), making it challenging to determine the trajectory of academic outcomes based on solely right vs left hemisphere injury.

Our regression results suggested that higher maternal education only predicted better mathematical performance and higher household income only predicted better verbal comprehension abilities. This may be partly due to the fact that verbal comprehension and mathematics domains are closely tied to language exposure and academic experience, making them particularly vulnerable to environmental influences. The lack of associations found between SES and other neurocognitive and academic measures contrasted with our hypotheses. Our sample showed limited variability and was skewed toward families with higher education and income levels, which may have masked potential differences in these other domains, especially domains that are less directly influenced by educational opportunities. It is well established in the literature that SES strongly influences neurodevelopment, including across brain injury and stroke populations (Bartha-Doering et al., 2021; Champigny et al., 2024; Venturini et al., 2024). The limited SES variability in our sample may have obscured differences in other domains; nevertheless, our significant findings highlight the educational relevance of verbal comprehension and mathematics.

Limitations and Future Directions

To our knowledge, our study is the first to examine the academic performance and predictors of academic outcome in the childhood hemorrhagic stroke population specifically. However, there are limitations to this study that must be acknowledged. The small sample size comprises a well-known and common limitation in this line of research due to the rarity of hemorrhagic stroke in childhood. The small number of participants limits the number and power of inferential analyses conducted, which is the key reason why analyses included qualitative descriptions of observed patterns and trends. While some results demonstrated statistical significance, other findings offered exploratory insights into potential developmental trends that warrant further investigation. Findings should be replicated in separate studies before establishing conclusions. In addition, due to the small sample size, we did not have sufficient statistical power to include multiple predictors within a single model and as a result, we were unable to assess the relative contribution and interactions between these predictors. Due to these challenges, as well as the rarity and diversity of childhood hemorrhagic stroke, it is essential to promote international collaboration through long-term projects, like the AHA/ASA-Bugher Center of Excellence in Pediatric Hemorrhagic Stroke grant (Sheth et al., 2022). Future larger and longitudinal studies could further explore the developmental trajectory of outcomes in this population. While we explored additional neurocognitive domains of attention and performance-based executive functioning, we were unable to examine the association between these outcomes and the predictors in an effort to limit the number of exploratory analyses. Finally, we did not explore predictors such as psychosocial factors, clinical post-stroke complications, and the impact of time since injury, despite knowledge that these factors may affect the neurocognitive and academic trajectory of the pediatric stroke population (O'Keeffe & Cogley, 2021).

Additionally, our sample was skewed toward higher income and maternal education. Future studies could explore these predictors, along with a closer examination of SES factors, such as access to additional educational resources, to gain a deeper understanding of the factors that support improvement in long-term academic and intellectual outcomes.

Conclusion

In conclusion, our study contributes to the body of research on the neurocognitive and academic outcomes after pediatric hemorrhagic stroke. We found neurocognitive vulnerabilities in this population across all domains, with pronounced challenges in divided attention. Importantly, our study is among the first to specifically assess academic outcomes in this population. While prior studies have primarily discussed the need for academic accommodations, we directly measured academic skills and identified significant weaknesses, particularly in mathematical calculation abilities. Further, our results contribute to understanding predictors of intellectual and academic abilities by highlighting the trends and implications of age at stroke, hemorrhage volume, laterality, and SES. Our findings emphasize the need for close neuropsychological follow-up in this population and for provision of early interventions and supports. Timely assessments are crucial for identifying children at risk of academic challenges and advocating for the necessary learning supports and resources. Further, our findings highlight the necessity for future research to continue to explore the complex impacts of clinical and demographic factors on brain development and neurodevelopmental outcomes.

Chapter 4: Predictors of Neurocognitive Outcome Following Childhood Hemorrhagic Stroke in the Left Hemisphere: A Case Series

Publication Status and Author Contributions

The following chapter is based on a manuscript which, has been published in the journal of *Applied Neuropsychology: Child*. The reference for this journal is as follow:

Kahnami, L., Champigny, C. M., Al-Hakeem, H., Desrocher, M., Butterfield, K. M., Désiré, N., Dlamini, N., Chowdhury, S.S., Dirks, P., & Westmacott, R. (2025). Predictors of neurocognitive outcome following childhood hemorrhagic stroke in the left hemisphere: A case series. *Applied Neuropsychology: Child*, 1-8. https://doi.org/10.1080/21622965.2025.2490101

Leila Kahnami, the first author, spearheaded the research efforts, which included conceptualizing the study, applying for approval from the Research Ethics Boards at the Hospital for Sick Children and York University, recruiting participants, collecting data, analyzing and interpreting the results, and writing the manuscript for publication.

Abstract

Neurocognitive deficits commonly occur following hemorrhagic stroke in childhood, yet the understanding of recovery patterns and prognostic factors remains limited. Hematoma location, lateralization, volume, and age at injury have been identified as predictors of neurocognitive outcomes. This case review aims to describe and discuss the influence of these factors on neurocognitive outcomes following hemorrhagic stroke in three pediatric cases. Three patients (one female age 13, two males ages 15 and 17) with a history of childhood hemorrhage were selected from a larger cohort due to their similar etiology (i.e., arteriovenous malformation) and similar lesion location (i.e., broadly within the temporoparietal region). Participants completed a neuropsychological assessment evaluating verbal comprehension, perceptual reasoning, processing speed, working memory, verbal fluency, language, learning, memory, and executive functioning. Results suggest variable language outcomes despite similar clinical characteristics. Both Case 1 and Case 2, who had medium-sized hematomas, exhibited challenges with verbal learning, verbal memory, word finding, and word generation. In contrast, Case 3, who had a small-sized hematoma, showed broadly preserved verbal abilities. All three cases exhibited challenges on at least one measure of executive functioning. The distinct performance of the three cases highlights the complexity of predicting neurocognitive abilities following childhood left hemisphere hemorrhagic stroke. The finding that all cases exhibited executive functioning deficits suggests an area of vulnerability in this population. Clinical implications include the importance of close monitoring and follow-up through comprehensive neuropsychological assessment in this population.

Introduction

Childhood strokes are significant contributors to pediatric acquired brain injury and can lead to various neurocognitive challenges (Chowdhury et al., 2022; Roach et al., 2008). The majority of survivors experience some degree of challenge in cognitive domains that may include language, attention, visuospatial skills, executive function, processing speed, and memory (Bolk et al., 2022; Bosenbark et al., 2018; Champigny et al., 2023a; Murphy et al. 2017; Peterson et al., 2019; Rivella & Viterbori, 2021; Westmacott et al., 2010, 2018). Neurocognitive impairments can also in turn impact academic achievement (Champigny et al., 2020; Hawks et al., 2016; Li et al., 2022; Peterson et al., 2019; Yvon et al., 2018). In addition, childhood stroke is associated with mental health concerns, including anxiety and depression (Champigny et al., 2023b; Ledochowski et al., 2020; O'Keeffe et al., 2017; Williams et al., 2017).

Hemorrhagic stroke specifically refers to bleeding in the brain caused by ruptured blood vessels, and accounts for about half of childhood strokes (Chowdhury et al., 2022). Vascular malformations are the most common risk factor associated with non-traumatic pediatric hemorrhagic strokes and account for approximately 48% of injuries (Gulati & Kalra, 2003). Arteriovenous malformations (AVM) are congenital or developmental vascular malformations in the brain, characterized by a nidus of abnormal blood vessels that form direct connections between arteries and veins (Lawton et al., 2015). In terms of neurocognitive outcomes following hemorrhagic stroke in childhood, the literature remains limited. Studies suggest that the performances of children with this medical history generally skew toward the clinically average (Blom et al., 2003; Murphy et al., 2017; Wingeier et al., 2011) to low average ranges (Yvon et al., 2018) on measures of overall intelligence. However, studies exploring neurocognitive performance within specific domains suggest that survivors of childhood hemorrhagic stroke

may face challenges in areas such as working memory and processing speed (Murphy et al., 2017). A recent study reveals that a higher-than-expected proportion of these children demonstrate scores that may fall in the lower ranges on measures of verbal learning, verbal memory, visuomotor integration, processing speed, working memory, and selective attention (Champigny et al., 2024).

There are gaps in scientific understanding of the predictors of neurocognitive outcomes in this medical population. Studies in the broader context of childhood stroke have identified several factors influencing neurocognitive outcome including lesion location, laterality, size, and age at injury. Injury locations can vary widely and often cross cortical and subcortical brain regions, complicating comparisons between subjects (Durston & Casey, 2006). Given the heterogeneity of lesion locations, researchers have primarily categorized strokes into subcortical, cortical, and combined types, leaving a gap in understanding specific regions affected (O'Keeffe et al., 2017). Mixed findings have emerged regarding the influence of injury laterality on neurocognitive outcomes in the pediatric population; the expected pattern of deficits apparent in adults with stroke may not apply to children (Kolk et al., 2011). Lateralization begins in the first months of life but has been shown to continue into adolescence and can be altered by neural reorganization following injury (Ilves et al., 2014). Some studies report no significant effect of the lesion side (Abgottspon et al., 2022; Bosenbark et al., 2017; Everts et al., 2008), while others report that lesions particularly in the left hemisphere can cause deficits in receptive language, verbal memory, working memory, and vocabulary (Allman & Scott, 2013; De Schryver et al., 2000; Funnell & Pitchford, 2010; Rowan et al., 2007). Injury size has also been identified as a predictor of neurocognitive outcomes, with more extensive lesions associated with worse outcomes compared to small and medium lesions (Abgottspon et al., 2022; Bartha-

Doering et al., 2021; Champigny et al., 2023a). Another predictor is age at injury, which continues to foster debate in the field of pediatric brain injury. Some researchers defend the plasticity hypothesis, which highlights the young brain's capacity for functional reorganization after injury (Abgottspon et al., 2022; Max et al., 2010), and others defend the vulnerability hypothesis, which points to the developing brain's higher susceptibility (Everts et al., 2008; Jacomb et al., 2018; Max et al., 2010; Peterson et al., 2019; Westmacott et al., 2010), with some studies suggesting that plasticity and vulnerability both contribute to neurocognitive outcomes (Anderson et al., 2011; de Montferrand et al., 2019).

The existing literature on childhood stroke is fragmented and the literature on pediatric hemorrhagic stroke specifically remains sparse. This case review describes the neuropsychological profile of three survivors of childhood hemorrhagic stroke, with similar etiology (i.e., AVM) and similar hematoma location and laterality (i.e., left temporoparietal region). The current study aims to describe clinical characteristics of these patients and discuss potential clinical predictors that influenced their neurocognitive profiles.

Materials and Methods

Participants

The three cases included in this review were part of a larger study exploring neurocognitive outcomes in childhood survivors of hemorrhagic stroke. Participants were seen for a neuropsychological routine follow-up in a tertiary hospital setting and consented to participate in the study. The neuropsychological testing was conducted in one day and lasted around 5 to 6hours. Three cases were selected for this review due to similar clinical factors. In all three cases, the hemorrhagic stroke was secondary to AVM and broadly affected the same brain region (i.e., left temporoparietal). All participants were fluent in English and attended school in

English. Two participants reported fluency in a second language spoken at home. They all received inpatient or outpatient rehabilitation after their discharge from acute care. All participants were right-handed. No family history of AVMs or cerebrovascular conditions was reported.

Ethical Considerations

The study was approved by the Research Ethics Board of Hospital for Sick Children in Toronto, Canada. Researchers explained the study goals and procedures to youth and their caregivers as part of the informed consent procedure. Written consent was gathered from all participating families.

Measures

Clinical variables were collected and coded via hospital medical records. Hemorrhage size was coded according to Beslow et al. (2014) Pediatric Intracerebral Hemorrhage Score. Hemorrhage volume and total brain volume were calculated via the ABC/XYZ method. The hematoma was classified as small (≤ 2% of TBV), medium (< 2–3.99% of TBV), or large (≥ 4% of TBV), by a pediatric neuropsychologist. Neurocognitive outcomes were quantified using index measures and scores on standardized neuropsychological tests assessing verbal comprehension, perceptual reasoning (i.e., visuo-spatial abilities and fluid reasoning), working memory, processing speed, verbal fluency, expressive and receptive language, aspects of executive function (i.e., inhibition switching and set shifting), and learning and memory (Table 8). All data are presented in standard scores. On neuropsychological measures, standard scores are classified following the classification system of the American Academy of Clinical Neuropsychology (Table 9; Guilmette et al., 2020).

Table 8

Neurocognitive Skills and associated Measures in Study 2

Neurocognitive skill	Standardized measure
Verbal comprehension	Verbal Comprehension Index (subtests: Similarities and Vocabulary) of the Wechsler Intelligence Scale for Children, 5th Edition (Wechsler, 2014) / Verbal Comprehension Index (subtests: Similarities and Vocabulary) of the Wechsler Adult Intelligence Scale, 4th Edition (Wechsler, 2008)
Perceptual reasoning	The mean of Visual Spatial (subtests: Block Design and Visual Puzzles) and Fluid Reasoning Indices (subtests: Matrix Reasoning and Figure Weights) of the Wechsler Intelligence Scale for Children, 5th Edition (Wechsler, 2014) / Perceptual Reasoning Index (subtests: Block Design and Matrix Reasoning) of the Wechsler Adult Intelligence Scale, 4th Edition (Wechsler, 2008)
Working memory	Working Memory Index (subtests: Digit Span and Picture Span) of the Wechsler Intelligence Scale for Children, 5th Edition (Wechsler, 2014) / Working Memory Index (subtests: Digit Span and Arithmetic) of the Wechsler Adult Intelligence Scale, 4th Edition (Wechsler, 2008)
Processing speed	Processing Speed Index (subtests: Coding and Symbol Search) of the Wechsler Intelligence Scale for Children, 5th Edition (Wechsler, 2014) / Processing Speed Index (subtests: Coding and Symbol Search) of the Wechsler Adult Intelligence Scale, 4th Edition (Wechsler, 2008)
Full scale IQ	FSIQ Index (subtests: Similarities, Vocabulary, Block Design, Matrix Reasoning, Figure Weights, Digit Span, Coding) of the Wechsler Intelligence Scale for Children, 5th Edition (Wechsler, 2014) / FSIQ Index (subtests: Similarities, Vocabulary, Block Design, Matrix Reasoning, Digit Span, Arithmetic, Symbol Search, Coding) of the Wechsler Adult Intelligence Scale, 4th Edition (Wechsler, 2008)
Verbal fluency	Letter and Category fluency: Letter fluency and category fluency scores of the NEPSY-II (Korkman et al., 2007)/ letter and category fluency score of Verbal Fluency task on D-KEFS (Delis et al., 2001) Word retrieval: Rapid Picture Naming score of the WJ-III (Woodcock et al., 2001)
Language	Expressive language: Score of the Expressive Vocabulary Test, Third Edition (EVT-3; Williams, 2019), which measures expressive one-word vocabulary Receptive Language: Score of the Peabody Picture Vocabulary Test, Fifth Edition (PPVT-5; Dunn, 2019), which measures receptive one-word vocabulary
Executive function	Inhibition Switching: Inhibition Switching score on the Inhibition task of the NEPSY-II (Korkman et al., 2007)/ Inhibition Switching score of the Color-Word Interference Test from the D-KEFS (Delis et al., 2001) Set Shifting: Trail Making Switching score of the Trail Making Test of the D-KEFS (Delis et al., 2001)
Learning	Rote Verbal Learning: Trials 1–5 total words recall score of the California Verbal Learning Test for Children (Delis et al., 1994) / Immediate free recall score of the California Verbal Learning Test, 3rd Edition (Delis et al., 2017) Contextualized Verbal Learning: Instruction score of the CHAMP (Sherman & Brooks, 2015)/ Logical Memory I score of the Wechsler Memory Scale, 4th Edition (WMS-IV) (Wechsler, 2009) Visual Learning: Objects score of the CHAMP (Sherman & Brooks, 2015)/ Design I score of the Wechsler Memory Scale, 4th Edition (WMS-IV) (Wechsler, 2009)
Memory	Rote Verbal Memory Delayed: Short delay free recall score of the California Verbal Learning Test for Children (Delis et al., 1994) / short delay free recall score of the California Verbal Learning Test, 3rd Edition (Delis et al., 2017) Rote Verbal Recognition: Recognition score of the California Verbal Learning Test for Children (Delis et al., 1994) / Recognition score of the California Verbal Learning Test, 3rd Edition (Delis et al., 2017) Contextualized Verbal Memory Delayed: Instruction Delayed score from the CHAMP (Sherman & Brooks, 2015)/ Logical Memory II score from the Wechsler Memory Scale, 4th Edition (WMS-IV) (Wechsler, 2009)

Table 9

Clinical Classification of Age-Normed Test Scores in Study 2

Classification	Range of percentiles	Range of standard scores
Exceptionally High	> 98th percentile	130+
Above Average	91st – 97th percentile	120-129
High Average	75th – 90th percentile	110-119
Average	25th – 74th percentile	90-109
Low Average	9th – 24th percentile	80-89
Below Average	~2nd – 8th percentile	70-79
Exceptionally Low	~< 2nd percentile	<70

Note. Standard score where *M* = 100 and *SD* = 15 in a normative sample.

Results

Demographic and clinical characteristics of the three cases are presented in Table 10, and neuropsychological test results in Table 11.

Table 10

Demographic and Clinical Characteristics of the Three Cases in Study 2

	Case 1	Case 2	Case 3
Sex	M	F	M
Age at injury	13.2 years	5.8 years	15.7 years
Age at testing	15.5 years	13.3 years	17.5 years
Prior Medical History	Brief possible seizure episodes, otherwise, otherwise unremarkable	Unremarkable	Unremarkable
Presenting symptoms	One-day history of two successive generalized tonic-clonic seizures, speech heaviness, disorientation, and headache	Four-day history of headache, nausea, vomiting, abdominal pain; one-day history	Two-day history of headache, confusion, and speech difficulty

		of speech difficulty and right-sided weakness	
Lateralization	Left	Left	Left
AVM Location	Middle temporal gyrus, fed by posterior temporal branches of PCA and temporal branches of MCA	Anterior basal temporal region	Along the lateral temporal surface fed by an MCA branch with a vein draining into the sigmoid sinus via Labbe
Hemorrhage Location	Temporo-parietal region	Temporo-parietal region	Temporo-parietal region
Hematoma Size Classification	Medium	Medium	Small
Surgical Procedure	Embolization, craniotomy for hematoma evacuation and AVM resection	Craniotomy for resection of the AVM and hematoma	Craniotomy for resection of the AVM and hematoma
Post-Surgery Symptoms	Challenges with expressive and receptive language; word-finding difficulties in all three spoken languages (French, Spanish, and English)	Challenges with expressive and receptive language (i.e., one-word responses with severe word retrieval difficulties)	Challenges with expressive and receptive language abilities; expressive aphasia (i.e., word retrieval difficulties)
Rehabilitation following surgery	Inpatient Rehabilitation including Speech Language Therapy	Outpatient Rehabilitation including Speech Language Therapy	Inpatient Rehabilitation including Speech Language Therapy
Medication at the time of testing	No	No	No
Handedness	Right	Right	Right
Physical/motor impairments at the time of testing	No	No	No
Special education Plan/Support at school	No	Yes	No

Case 1

Case 1 completed a neuropsychological assessment at 15.5 years of age, two years post-injury (age at injury: 13.2). Results indicated well-developed overall intellectual abilities (i.e., full-scale IQ) with perceptual reasoning falling within the high average range and verbal comprehension, working memory, processing speed, inhibition switching, and set shifting falling within the average range. In contrast, he demonstrated profound challenges with word finding and word generation, performing in the exceptionally low range. Further, his ability to effectively learn and remember new information appeared to have been impacted by his stroke, with particular difficulty in contextualized and rote verbal learning (i.e., exceptionally low range). Despite average intellectual abilities and many well-preserved neurocognitive abilities, Case 1's profile is suggestive of significant challenges with verbal neurocognitive abilities, specifically word generation, word retrieval, and verbal learning and memory.

Case 2

Case 2 completed a neuropsychological assessment at 13.3years of age, eight years post-injury (age at injury: 5.8). Results indicated that Case 2's overall intellectual abilities (i.e., full-scale IQ) fell in the low average range. She performed within the low average to average range on measures of perceptual reasoning, working memory, inhibition switching, and verbal and visual learning and memory. In contrast, Case 2's receptive language abilities fell in the extremely low range, and she performed within the below average range on measures of verbal comprehension, processing speed, expressive language, set shifting, and verbal fluency. Case 2's profile indicates challenges in verbal neurocognitive abilities such as verbal comprehension, word finding, word generation, and expressive language abilities, along with exceptionally low receptive language abilities. It is notable that she is the youngest of the participants to have sustained a stroke.

Case 3

Case 3 completed a neuropsychological assessment at 17.5years of age, two years post-injury (age at injury: 15.7). Results indicated well-developed overall intellectual abilities (i.e., full-scale IQ), with verbal comprehension, perceptual reasoning, processing speed, verbal fluency and retrieval, inhibition switching, set shifting, and verbal and visual learning and memory all falling within the average to above average ranges. Case 3 performed in the low average range on measures of working memory. Overall, Case 3's profile includes age-appropriate intellectual abilities and well-preserved verbal neurocognitive abilities, and a weakness in working memory.

Table 11

Neurocognitive Performance of the Three Cases in Standard Scores in Study 2

Cognitive domain	Case 1		Case 2		Case 3	
Intellectual abilities	Classification	Standard score	Classification	Standard score	Classification	Standard score
Verbal comprehension	Average	92	Below Average	70	Average	100
Perceptual reasoning	High Average	111	Average	90	Average	100
Working memory	Average	93	Average	105	Low Average	82
Processing speed	Average	100	Below Average	77	Average	100
Full scale IQ	Average	95	Low Average	80	Average	95
Verbal fluency						
Letter fluency	Below Average	70	Average	100	Average	105
Category fluency	Exceptionally Low	55	Below Average	75	Average	105
Word retrieval	Exceptionally Low	53	Below Average	77	Average	107
Language						
Receptive language		N/A	Exceptionally Low	65		N/A
Expressive language		N/A	Below Average	72		N/A
Executive function						
Inhibition switching	Average	95	Average	105	High Average	115
Set shifting	Average	95	Below Average	75	Average	105
Learning and memory						
Rote verbal learning	Exceptionally Low	65	Average	96	High Average	119

Rote verbal delayed recall	Below Average	78	Average	92	Above Average	120
Rote verbal recognition	Average	108	Average	100	High Average	115
Contextualized verbal learning	Exceptionally Low	60	Low Average	80	Average	100
Contextualized verbal memory delayed	Exceptionally Low	55	Low Average	80	Average	100
Visual learning	Low Average	80	Low Average	85	Average	105
Visual memory delayed	Below Average	75	Average	95	Average	90

Discussion

The three cases presented in this review sustained a hemorrhage secondary to AVM rupture affecting the left temporoparietal region, a brain area that is integral to language processing and sensory integration (Gesierich et al., 2012). Despite similarity of injury etiology, location, and laterality, all three cases exhibited a distinct neuropsychological profile. Cases 1 and 2, who had medium-sized hematomas, demonstrated neuropsychological profiles aligned with those of adults with left hemisphere injury, including challenges in verbal cognition such as verbal comprehension, verbal learning, verbal memory, word finding, and word generation (Lezak et al., 2004). In contrast, Case 3, who had a small-sized hematoma, exhibited preserved verbal abilities. Case 1's AVM was located in the left middle temporal gyrus, a structure that is heavily involved in language comprehension and semantic processing (Hickok, 2009). Case 1's AVM was primarily fed by posterior temporal branches from the posterior cerebral artery (PCA) and temporal branches from the middle cerebral artery (MCA). The involvement of both PCA and MCA suggests a significant vascular burden, which may explain the persistent difficulties in word retrieval and verbal tasks observed in this case. The AVM in Case 2 was located in the anterior basal part of the left temporoparietal region, generally associated with complex semantic processing and detailed aspects of language comprehension (Friederici, 2011), which may explain the pronounced challenges in language processing. Lastly, Case 3's AVM was located on the left lateral temporal surface, a brain region associated with language processing (Hickok,

2009), yet he showed preserved verbal abilities. It is possible that the small size of the hematoma allowed him to preserve these abilities. The distinct neuropsychological profiles of these three cases support the notion that predicting verbal deficits following childhood left hemisphere stroke is challenging (Kolk et al., 2011) and underscore the influence of factors beyond hematoma laterality, location, and volume.

There is scientific consensus that the developmental stage of the brain at the time of injury influences neurocognitive outcome, but findings have been inconsistent regarding the shape and direction of that relationship. Recent studies support the idea that both plasticity and vulnerability mediate neurocognitive outcome (Anderson et al., 2011), depending on the cognitive domain in question (Abgottspon et al., 2022). Some studies suggest poorer language prognosis for early lesions compared to later lesions (Avila et al., 2010; Chapman et al., 2003; Kolk et al., 2011; Lansing et al., 2004; Max et al., 2010; Westmacott et al., 2010), consistent with the vulnerability hypothesis. Aligned with this hypothesis, Case 2 exhibited language challenges across various verbal domains and is also the participant who sustained a stroke at the youngest age of all three, Case 1, who sustained a stroke at 13 years of age, and Case 2, who sustained a stroke at 5 years of age, both experienced persistent challenges in some common aspects of language (i.e., word generation and word retrieval). However, Case 2 exhibited challenges with concrete language tasks (i.e., expressive language, receptive language, and verbal comprehension), while other language-based abilities (i.e., verbal learning and memory) are generally age-appropriate. Case 1 exhibited challenges with verbal learning and memory, while verbal comprehension abilities are age-appropriate. These differences are consistent with the theory that both plasticity and vulnerability mediate outcomes (Anderson et al., 2011). Case 1 and Case 3's neurocognitive results reveal important differences despite both sustaining injuries

in adolescence (ages 13.2 and 15.7, respectively). Case 3 demonstrated age-appropriate abilities in verbal performance and language, whereas Case 1 continued to face persistent challenges in verbal domains. These findings align with a recent study which reported no significant associations between the age at injury and the language outcomes in children with left hemisphere strokes (de Montferrand et al., 2019). Plasticity and vulnerability could both play a role after left hemisphere damage, highlighting the complexity of predicting the recovery paths of children sustaining hemorrhagic stroke despite similarly affected lesion locations and age.

The results of this descriptive study suggest mild-to-moderate difficulties in tasks associated with executive functioning in all three cases. This finding contrasts with previous research that has reported better executive functioning prognosis for younger survivors of childhood stroke (Max et al., 2010; O'Keeffe et al., 2014). Case 1 demonstrated challenges with verbal fluency, Case 2 with verbal fluency and set shifting, and Case 3 with working memory. The neuropsychological profile of the three cases is consistent with research suggesting that damage to non-frontal cortical areas can result in neurocognitive challenges typically associated with prefrontal damage (Long et al., 2011; Whigham & O'Toole, 2007). This observation may be explained by the numerous afferent and efferent pathways linking the prefrontal cortex to cortical and subcortical regions as well as the prefrontal cortex's prolonged myelination and maturation that extends into adulthood (Funahashi, 2022). Damage to non-frontal areas connected with the prefrontal cortex can therefore indirectly impact the development of this region and render executive functioning abilities particularly vulnerable to early brain insult.

Limitations and Future Directions

Like many case studies, this manuscript faces several limitations. First, the results are not generalizable due to the small numbers included in the review and the inability to conduct

inferential analyses. Future research should investigate the influence of age at injury, hematoma volume, hematoma location and laterality, and other factors on neurocognitive outcomes following childhood hemorrhagic stroke in a larger sample. Due to the heterogeneity of childhood hemorrhagic stroke, it is paramount to foster international collaboration through ongoing projects, such as those at the AHA-Bugher Center for Brain Vascular Malformations, to advance our understanding of childhood hemorrhagic stroke. Further, we did not explore individual variability in non-clinical (i.e., environmental) factors, clinical post stroke complications, and the impact of time since injury on the neurocognitive trajectory in the pediatric stroke population despite knowledge that these factors affect neurocognitive outcomes. This decision was made due to the small sample size. For example, socioeconomic status has been associated with neurocognitive outcomes following pediatric stroke (Bartha-Doering et al., 2021; Champigny et al., 2023a), and home environment and family functioning have been associated with outcomes following pediatric acquired brain injury (Greenham et al., 2015; LeBlond et al., 2021; Semrud-Clikeman, 2010). Fatigue and headaches are also common post-stroke complications in childhood survivors (O'Keeffe & Cogley, 2021), which may contribute to the challenges with executive functioning. Future research on childhood hemorrhagic stroke should adopt a comprehensive approach, such as a biopsychosocial framework, to investigate the nuanced association between these clinical and non-clinical factors that affect neurocognitive outcomes.

Conclusion

The current descriptive study builds on the limited knowledge base about neurocognitive outcomes following childhood hemorrhagic stroke. By examining the neuropsychological profile of these three cases in detail, we can appreciate the nuances involved in estimating prognosis

regarding neuropsychological functioning following childhood stroke in clinical practice. The distinct verbal performance of the three cases challenges the previous literature on the association between injury laterality and neurocognitive outcome. The finding that all cases exhibited some degree of executive functioning challenges aligns with the notion that these skills require the coordination of a highly interconnected network of cortical and subcortical regions; as such, executive functioning is particularly vulnerable to impairment in the event of a stroke, as the injury can disrupt any part of this extensive network. Understanding the predictors of neurocognitive outcomes following childhood stroke is essential to improve prognosis evaluations and provide quality clinical care to affected families.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The primary author (L.K.) wishes to thank the Social Sciences and Humanities Research Council of Canada (SSHRC) for their support of this research.

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Note. The references below correspond only to Chapter 4, as they appear in the published version of this manuscript. The references for Chapters 1, 2, 3, 5, and 6 are provided at the end of this dissertation.

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Chapter 5: Health-Related Quality of Life Outcomes Following Childhood Hemorrhagic Stroke: Patterns and Predictors

Publication Status and Author Contributions

The following chapter is based on a manuscript which, as of October 2025, is in preparation for submission for publication to the journal of *Developmental Medicine & Child Neurology*. Currently, the reference for this manuscript is as follows:

Kahnami, L., Champigny, C. M., Beribisky, N.,Desrocher, M., Butterfield, K. M., Désiré, N., Dlamini, N., Chowdhury, S.S., Dirks, P., & Westmacott, R. (2025). Health-Related Quality of Life Outcomes Following Childhood Hemorrhagic Stroke: Patterns and Predictors [Manuscript in preparation for submission for publication]. Department of Psychology, York University.

Leila Kahnami, the first author, spearheaded the research efforts, which included conceptualizing the study, applying for approval from the Research Ethics Boards at the Hospital for Sick Children and York University, recruiting participants, collecting data, analyzing and interpreting the results, and writing the manuscript for publication.

Abstract

Aim: To characterize and examine potential predictors of health-related quality of life (HRQoL) after childhood hemorrhagic stroke.

Method: 24 patients (12 female, ages 5-18 years) with childhood hemorrhagic stroke participated in this study at Hospital for Sick Children in Toronto, Canada. HRQoL was evaluated using the KIDSCREEN-52, a parent questionnaire. Dimensions included physical well-being, psychological well-being, moods and emotions, social support and peers, and school environment. Predictors of age at stroke, socioeconomic status, full-scale intelligence, and executive functions were examined.

Results: The parent-rated HRQoL of participants was lower only for physical well-being, with no significant difference from the norms on the other dimensions. Age at stroke and socioeconomic status did not influence HRQoL. Emerging trends of a quadratic relationship between age at stroke and physical well-being, psychological well-being, moods and emotions, and school environment were observed. Lower FSIQ predicted poorer HRQoL in the social support and peers domain. Lower executive functioning was associated with all five dimensions.

Interpretation: Survivors of childhood hemorrhagic stroke have lower physical well-being, and those with poor executive functioning are at higher risk of low HRQoL overall. Stroke in middle childhood specifically appears to be associated with lower HRQOL, a finding that warrants further investigation.

Introduction

Childhood stroke is an important cause of disability in youth (Gordon, 2014), defined as a stroke occurring between the ages of 28 days and 18 years (Ferriero et al., 2019). Hemorrhagic stroke refers to bleeding caused by ruptured cerebral vessels (Askarova & Zhurkabayeva, 2024). Most childhood hemorrhagic strokes are caused by structural lesions, most commonly arteriovenous malformations in the brain (Ferriero et al., 2019). Childhood stroke has an incidence of 2 to 13 in 100 000 per year (Askarova & Zhurkabayeva, 2024; Ferriero et al., 2019), with hemorrhagic stroke accounting for half of childhood stroke incidences. Hemorrhagic stroke has received less attention in pediatric research than ischemic stroke (Ferriero et al., 2019). It was previously associated with a higher initial mortality rate but a lower likelihood of experiencing severe neurological or neuropsychological impairments relative to ischemic stroke (Lo et al., 2008). However, emerging evidence suggests that a substantial proportion of survivors of childhood hemorrhagic stroke face neurological, cognitive, academic, and psychosocial challenges (Champigny et al., 2025; Chowdhury et al., 2022; Kahnami et al., 2025; C. Murphy et al., 2017; Yvon et al., 2018). Importantly, as childhood stroke survivors grow and develop, and physical and cognitive demands increase over time, neurocognitive deficits may emerge long after the initial acute injury (Hebert et al., 2016). The evolving neurocognitive challenges can disrupt academic progress, social participation, and emotional well-being, ultimately leading to a lower health-related quality of life (HRQoL) (Gordon, 2014).

HRQoL is recognized as an important outcome measure for chronic diseases such as stroke, measuring physical, psychological, and school and social well-being, in line with the International Classification of Functioning, Disability and Health (World Health Organization, 2001). The existing literature on HRQoL in pediatric stroke presents mixed results. Some studies

report lower overall HRQoL, with challenges across all domains including physical, psychological, school, and social functioning (Cnossen et al., 2010; Fong et al., 2025; Friefeld et al., 2011; Ghotra et al., 2018; Lo et al., 2013; Neuner et al., 2011; O'Keeffe et al., 2012), while others indicate that HRQoL remains intact (Caspar-Teuscher et al., 2019; Darteyre et al., 2014; Rohner et al., 2020; Simma et al., 2007). Given the discrepancy in results, further research is warranted.

There is considerable evidence that functional outcomes vary based on clinical and demographic factors. Factors such as age, socioeconomic status (SES), and cognitive abilities have been associated with HRQoL in pediatric stroke populations, but reports of these associations are mixed (Cnossen et al., 2010; Friefeld et al., 2011; Ghotra et al., 2015; Neuner et al., 2011; Simma et al., 2007), and data on childhood survivors of hemorrhagic stroke are lacking.

The primary aim of this study is to characterize the HRQoL in survivors of childhood hemorrhagic stroke. The secondary aim is to determine whether clinical and demographic predictors – age at stroke, SES, intellectual abilities, and executive functioning abilities – predict HRQoL outcomes in this population.

Materials and methods

Participants

The hospital's neurovascular program's database was used to identify childhood hemorrhagic stroke patients with a hematoma documented on magnetic resonance imaging or computed tomography. Inclusion criteria consisted of a history of non-traumatic hemorrhagic stroke occurring between the ages of 28 days and 18 years, 5 to 18 years of age at the time of participation, at least six months post-stroke at the time of participation, and proficiency in

English. Exclusion criteria included unstable medical condition and inability to complete neuropsychology measures (e.g., due to severe intellectual disability). Participants completed a series of neuropsychological tests. All scores were determined relative to age norms. Measures were administered, scored, and interpreted by clinical pediatric neuropsychologists or senior Ph.D. students in clinical pediatric neuropsychology. Demographic variables were gathered through a background questionnaire completed by caregivers and clinical variables were coded via hospital medical records.

Ethical Considerations

The study was approved by the Research Ethics Board of Hospital for Sick Children in Toronto, Canada. Researchers explained the study goals and procedures to youth and their caregivers as part of the informed consent procedure. Written caregiver consent and participant assent or consent were gathered from all participating families.

Health-Related Quality of Life Measure

Health-related quality of life (HRQoL) was evaluated using a proxy parent version of KIDSCREEN-52 (Ravens-Sieberer et al., 2005). The instrument consists of 52 items assessing ten dimensions of well-being: physical well-being, psychological well-being, moods and emotions, self-perception, autonomy, parent relations and home life, social support and peers, school environment, bullying, and financial resources. Parents provided their responses using a 5-point Likert scale, and the raw scores were then converted into T-scores (M= 50, SD = 10), where higher scores indicate a better perceived HRQoL. The scale demonstrates adequate psychometric properties in terms of reliability and validity (Herdman et al., 2007; Ravens-Sieberer et al., 2001). To reduce the likelihood of Type I error due to multiple comparisons, five out of the ten dimensions were selected for analyses: physical well-being, psychological well-

being, moods and emotions, social support and peers, and school environment. These dimensions were selected as outcome measures for this study based on their theoretical relevance as defined by the International Classification of Functioning, Disability and Health (World Health Organization, 2001) and in line with similar measures of HRQoL used in pediatric stroke populations (Ghotra et al., 2015; Neuner et al., 2011; Freifeld et al., 2011).

Predictor Variables

Age at Stroke

Age at stroke was calculated based on the date of clinical presentation. Participants were categorized into three age groups: early childhood (stroke at 28 days to <6 years), middle childhood (6 years to <12 years), and adolescence (12 years to ≤18 years).

Socioeconomic Status (SES)

SES was defined by household income as reported by caregivers on a 6-point scale ranging from less than $25,000 (i.e., ~$18,000 USD at the time of testing) to greater than $150,000 CAD (i.e., ~$110,000 USD).

Full-Scale IQ (FSIQ)

Global intellectual ability was represented by the FSIQ. The Wechsler Preschool and Primary Scale of Intelligence, 4th Edition (Wechsler, 2012) was administered to children younger than 6 years, the Wechsler Intelligence Scale for Children, 5th Edition (Wechsler, 2014) to children aged 6 to 16 years, and the Wechsler Adult Intelligence Scale, 4th Edition (Wechsler, 2008) for children 16 years and older. FSIQ is in the form of a standard score (M=100, SD=15) and is calculated relative to age-based norms. The FSIQ includes verbal comprehension (i.e., verbal reasoning, vocabulary), perceptual reasoning (i.e., nonverbal abstract reasoning, visual-

spatial skills), working memory (i.e., ability to mentally hold and manipulate information), and processing speed (i.e., speed and efficiency of mental processing).

Global Executive Composite (GEC)

Overall executive functioning abilities were obtained by the GEC of the Behavior Rating Inventory of Executive Function, 2nd Edition (BRIEF-2; Gioia et al., 2015), a standardized parent-report questionnaire. GEC scores are T-scores (M=50, SD=10) calculated relative to age-based norms. A higher T-score indicates more challenges overall in executive functioning abilities. Executive functioning abilities are the brain's self-management tools that help a person regulate their thinking (e.g., multi-task, plan and organize), their emotions (e.g., cope with strong emotions), and their behaviour (e.g., inhibit impulses).

Statistical Analysis

All analyses were performed using R (v4.2.1), with statistical significance set at $p < .05$ and confidence intervals set at 95%. Descriptive statistics were used to describe the demographic and clinical characteristics of the sample. The mean T-scores and standard scores of the HRQoL variables, FSIQ, and GEC were calculated. The proportion of children scoring within the below average range (1 *SD* to 2 *SD* below the mean, i.e., 30 ≤ T-score <40) or extremely low range (2 *SD* or more below the mean, i.e., T-score <30) for each HRQoL domain was calculated.

HRQoL variables were examined to ensure that parametric assumptions were met. Shapiro-Wilk test and Q-Q plots informed the normality of data distribution. A series of one-sample *t*-tests were conducted to compare the parent rating of HRQoL domains of the hemorrhagic stroke sample with the norms. Cohen's d statistics were computed as a measure of effect size to quantify the difference between the childhood hemorrhagic stroke sample and normative mean (Cohen, 1988).

A series of univariate linear regressions investigated relationships between HRQoL and age at stroke, household income, FSIQ, and GEC. The overall model fit (*F*-statistic, *p*-value, and R^2) and individual parameter estimates (unstandardized beta coefficients, standard errors, and *p*-values) are provided for each linear regression. Descriptive comparisons were used with locally estimated scatterplot smoothing (LOESS) for age at stroke and boxplots for the three age groups.

Results

Participants included 24 (50% female) children with a history of hemorrhagic stroke. The mean age at stroke onset was 7.98 years (*SD* = 4.63), with 38% of participants sustaining hemorrhagic stroke in early childhood (28 days to <6 years), 29% in middle childhood (6 years to <12 years), and 33% in adolescence (12 years to ≤18 years). About half of families (54.16%) reported a household income above $100,000. Additional demographic and clinical characteristics were also collected (Table 12).

Table 12

Demographic and Clinical Characteristics of the Hemorrhagic Stroke Sample (n=24) in Study 3

Sex *n (%)*	
Female	12 (50.0%)
Male	12 (50.0%)
Native language *n (%)*	
English	18 (75.0%)
Other	6 (25.0%)
Number of languages spoken at home *n (%)*	
English only	10 (41.67%)
English and other languages	14 (58.33%)
Age at assessment (years) *M* (*SD*)	12.02 (3.76)
Handedness *n (%)*	
Right	21 (87.50%)
Left	3 (12.50%)
Family income	
$25,000 - $49,999	3 (12.50%)
$50,000 - $74,999	4 (16.67%)
$75,000 - $99,999	4 (16.67%)
$100,000 - $149,999	4 (16.67%)
Over $150,000	9 (37.50%)
Age at stroke (years) *M* (*SD*)	7.98 (4.63)

Stroke onset age group *n (%)*	
Early childhood (1 month to 6 years)	9 (37.50%)
Middle childhood (6 to 12 years)	7 (29.17%)
Adolescence (12 to 18 years)	8 (33.33%)
Time since stroke (years) *M* (*SD*)	4.03 (3.34)
Type hemorrhagic stroke *n (%)*	
Intracerebral hemorrhage (ICH)	22 (91.67%)
Subdural hemorrhage (SDH)	1 (4.17%)
Subarachnoid hemorrhage (SAH)	1 (4.17%)
Hemorrhage location *n (%)*	
Laterality	
Left hemisphere	12 (50.0%)
Right hemisphere	11 (45.83%)
Bilateral	1 (4.17%)
Region	
Supratentorial	13 (54.16%)
Infratentorial	5 (20.83%)
Intraventricular	3 (12.50%)
Combined (supra- and infratentorial)	2 (8.33%)
Size *n (%)*	
Small	9 (37.50%)
Medium	9 (37.50%)
Large	4 (16.67 %)
N/A	2 (8.33%)
Hemorrhage etiology *n (%)*	
AVM (vascular malformations)	15 (62.50%)
Cavernoma (vascular malformations)	2 (8.33%)
Cortical vein thrombosis (CVST)- venous abnormalities	1 (4.17%)
Idiopathic	6 (25.0%)

The mean overall FSIQ was 88.58 (*SD*=16.85), indicating a notable reduction in general intellectual functioning relative to population norms. Nonetheless, a mean FSIQ of 88.58 is within one standard deviation (i.e., 15) of the population average (i.e., 100), suggesting relative preservation of overall intellectual functioning in many individuals in our sample. The mean overall GEC was 57.10 (*SD*=13.56), (Table 13).

Table 13

Intellectual and Executive Functioning Performance of the Sample in Study 3

Intellectual	*M* (*SD*) standard score[a]
Verbal comprehension	87.67 (17.33)
Perceptual reasoning	95.56 (17.40)
Working memory	87.08 (16.38)
Processing speed	89.67 (19.50)
Full scale IQ	88.58 (16.85)
Executive function	*M* (*SD*) T score[b]
Behavioural regulation	53.10 (12.21)
Emotional regulation	56.52 (12.99)
Cognitive regulation	58.67 (14.47)
Global executive composite	57.10 (13.56)

Note. [a]Standard score where *M* = 100 and *SD* = 15 in a normative sample; [b]T score where *M* = 50 and *SD* = 10 in a normative sample, with higher T scores indicating more executive functioning challenges.

T-test results revealed that the hemorrhagic participants performed significantly lower than the normative mean on the dimension of physical well-being (mean difference -6.68, $p = .022$). There was no significant difference compared to the norms on dimensions of psychological well-being, moods and emotions, social support and peers, and school environment (Table 14). Despite the overall average mean in most domains of HRQoL, a higher proportion of participants scored in the below average and extremely low ranges than expected in a normally distributed group (Figure 4 and Table 14). For example, on the dimension of moods and emotions, 25% of the sample scored in the below average range compared to 14% expected in population norms.

Table 14

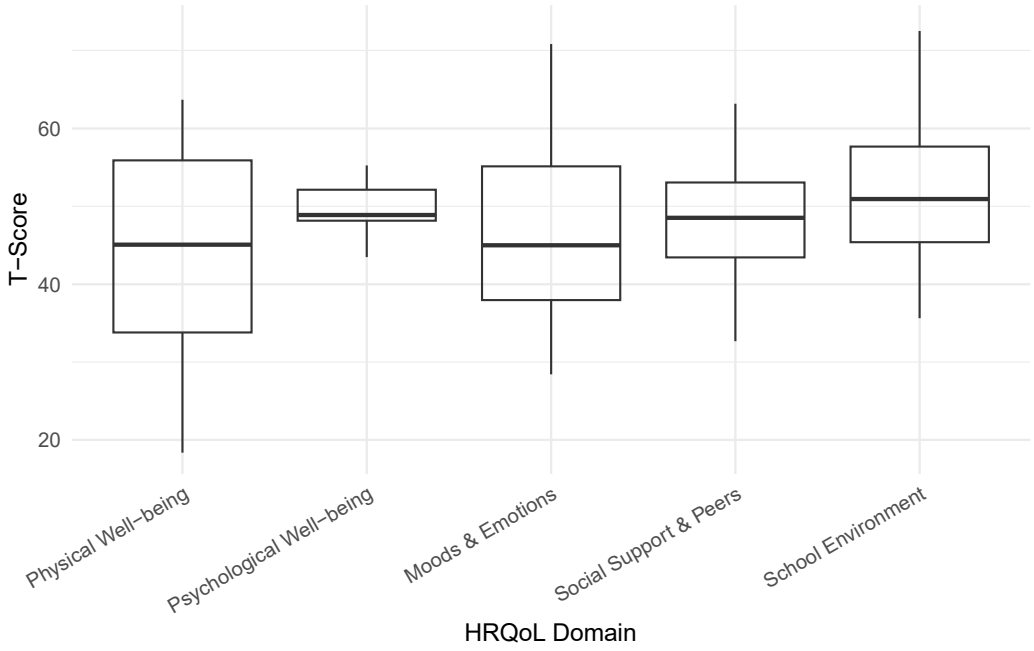
The Parent-Reported HRQoL Functioning: Mean Scores and One-Sample t-Test Results Comparing the Childhood Hemorrhagic Stroke Sample with the Normative Means in Study 3

HRQoL domain	*M* (*SD*)	95% *CI*	*t*	df	*p*	Cohen's *d*	Below average *n* (%)	Extremely low range *n* (%)
Physical well-being	43.32 (13.34)	36.18- 47.86	-2.45	23	**.022**	-0.61	7 (29.2%)	3 (12.5%)
Psychological well-being	49.58 (8.90)	45.27- 53.45	-0.23	23	.82	-0.07	3 (12.5%)	1 (4.2%)
Moods and emotions	46.84 (10.98)	41.6- 51.66	-1.41	23	.17	-0.30	6 (25.0%)	1 (4.2%)
Social support and peers	49.27 (10.37)	44.12- 52.51	-0.35	23	.73	-0.18	4 (16.7%)	0 (0%)
School environment	51.14 (11.55)	45.59- 55.84	0.48	23	.63	0.06	4 (16.7%)	1 (4.2%)

Note. Bold indicates statistical significance at $p < .05$; all scores are T scores ($M = 50$, $SD = 10$), with lower T scores indicating more challenges; df = degrees of freedom; below average is defined as a T score of 30 to 40, and extremely low is defined as a T score of less than 30.

Figure 4

Boxplots of the Parent-Reported HRQoL in the Childhood Hemorrhagic Stroke Sample in Study



Age at stroke was not found to be significantly associated with any HRQoL domains (Table 15). The sample showed relatively comparable medians on all HRQoL dimensions across early childhood (*n*=9), middle childhood (*n*=7), and adolescence (*n*=8) age groups, with the exception of physical well-being. On the physical well-being dimension, the middle childhood group had the lowest median, suggesting more physical HRQoL challenges for those sustaining stroke in middle childhood (Figure 5). Across most dimensions (i.e., moods and emotions, psychological well-being, and school environment), the middle childhood and adolescence groups showed greater variability in scores than the early childhood group, suggesting that there are likely additional factors influencing these HRQoL domains in the older age groups. Exploring age at stroke as a continuous variable, LOESS scatterplots revealed U-shaped patterns for physical well-being, psychological well-being, moods and emotions, and school environment, and an inverted U-shaped pattern for social support and peers domain (Figure 6). In other words, participants who sustained stroke around middle childhood generally scored lower than their peers (who had a stroke earlier or later in their youth) on all dimensions with the exception of social support and peers. The fitted trend lines for physical well-being, psychological well-being, moods and emotions, and school environment illustrate lowest ratings when strokes occurred between the ages of 8 and 10). The opposite pattern was observed for the domain of social support and peers, wherein children aged 8 to 10 showed the best outcomes. Despite the observed trends, confidence intervals were relatively wide for all five domains, indicating variability across all ages.

Table 15

Univariate Linear Model Results Exploring the Association Between Age at Stroke, Household Income, FSIQ, and GEC with Parent-Reported HRQoL Functioning in Study 3

HRQoL domain	Predictor	*Beta*	*p*	R^2
Physical well-being				
	FSIQ	0.27	0.11	0.12
	GEC	-0.49	**0.020***	0.25
	Household income	-2.10	0.28	0.05
	Age at stroke	-0.50	0.42	0.03
Psychological well-being				
	FSIQ	0.07	0.52	0.02
	GEC	-0.38	**0.003****	0.38
	Household income	0.70	0.59	0.01
	Age at stroke	-0.47	0.25	0.06
Moods and emotions				
	FSIQ	0.20	0.14	0.10
	GEC	-0.46	**0.002****	0.41
	Household income	-1.41	0.37	0.04
	Age at stroke	-0.40	0.43	0.03
Social support and peers				
	FSIQ	0.27	**0.031***	0.20
	GEC	-0.42	**0.016***	0.27
	Household income	2.20	0.14	0.10
	Age at stroke	-0.56	0.24	0.06
School environment				
	FSIQ	0.23	0.11	0.11
	GEC	-0.50	**0.008****	0.32
	Household income	1.14	0.50	0.02
	Age at stroke	-0.16	0.77	0.004

Note. Significant results are bolded; *$p < .05$. **$p < .01$.

Figure 5

Boxplots of the Parent-Reported HRQoL in the Childhood Hemorrhagic Stroke Sample by Age Group in Study 3

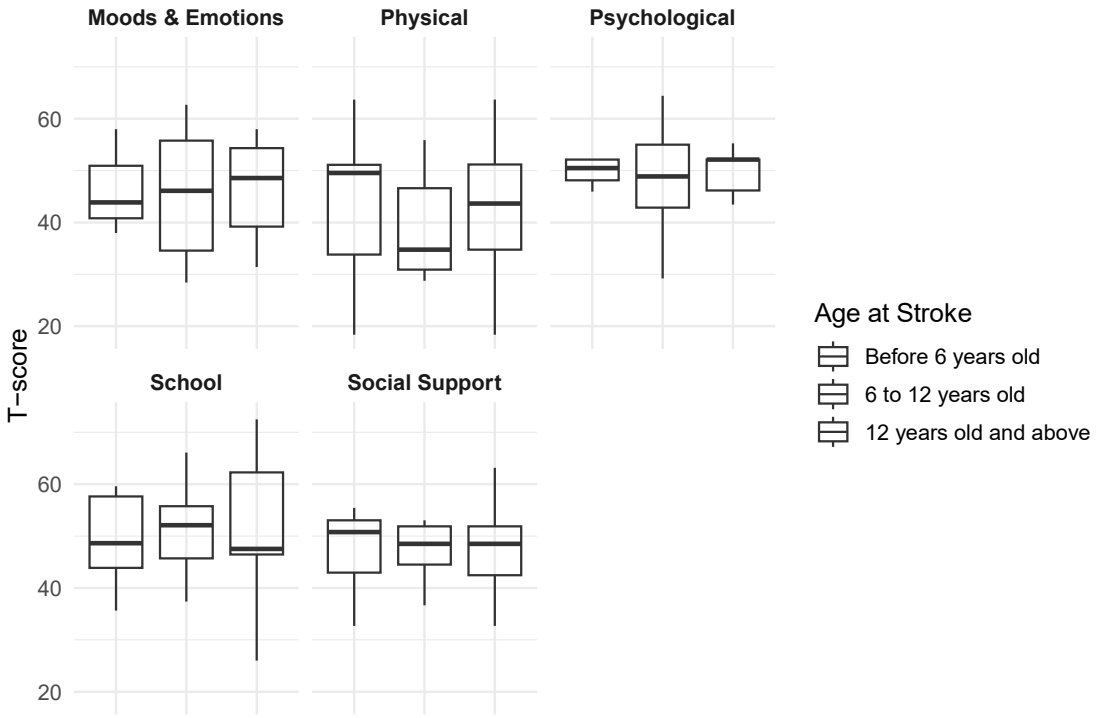
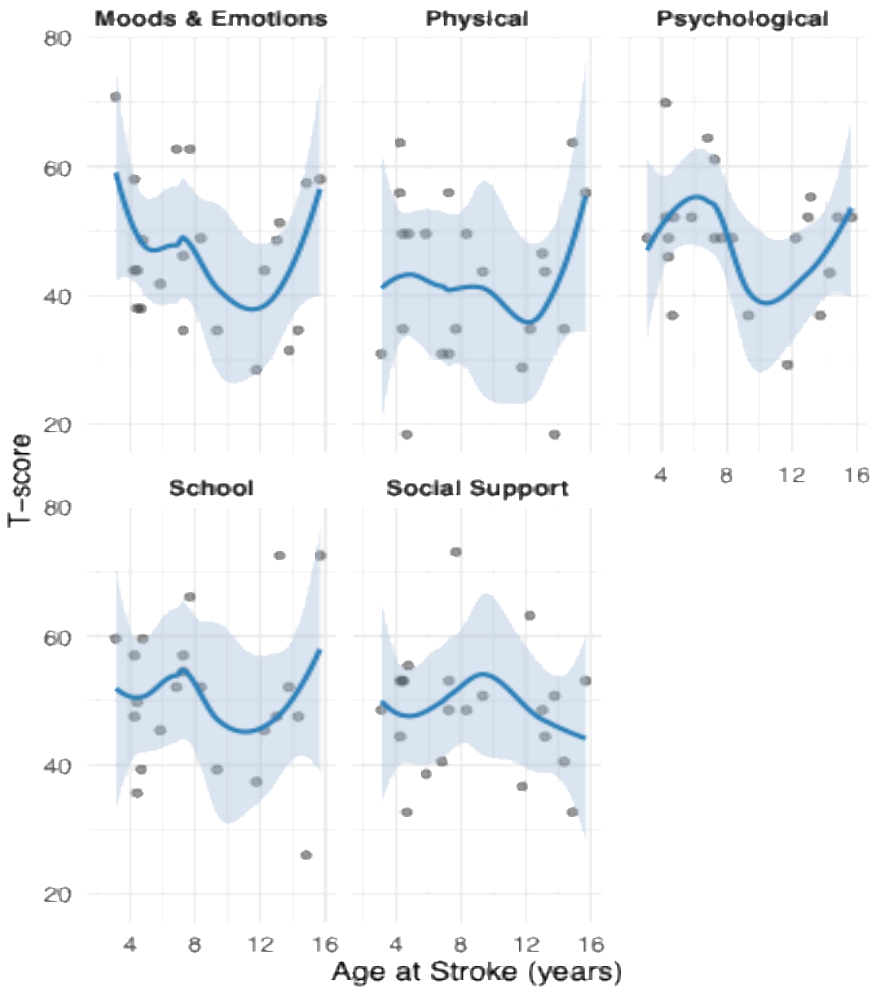


Figure 6

LOESS-Smoothed Scatterplots of Parent-Reported HRQoL Domains as Function of Age at Stroke in Study 3



Note. X-axis represents age at stroke (in years). 95% confidence interval in light blue. .

In univariate analysis, household income was not found to be significantly associated with any of the HRQoL domains. Higher FSIQ was associated with better HRQoL functioning in the social support and peer relationship domain, accounting for 20% of the variance in scores. Among the predictors examined, GEC stood out as the most consistently associated with the different domains of HRQoL. Higher GEC (i.e., more overall executive functioning challenges)

was associated with lower physical well-being, psychological well-being, moods and emotions, social support and peer relationship, and school environment, explaining between 25% to 41% of the variance in these domains. (Table 15).

Discussion

Parents rated the HRQoL of participants with childhood hemorrhagic stroke as significantly lower compared to normative data on the dimension of physical well-being. These results suggest lower perceived physical health, energy, and vitality, as well as reduced participation in physical activity and fitness routines. This mirrors findings in the current pediatric stroke literature. Pediatric stroke often results in mild to severe changes in gross and fine motor skills, such as hemiparesis and muscle weakness, which can affect balance and coordination (Svensson et al., 2022). These limitations in motor function are found to be ongoing in the majority of childhood stroke survivors, persisting long term (Greenham et al., 2021). Fatigue is also a particularly prevalent concern, with a study showing that 21% of youth with ischemic stroke experience challenges with fatigue and low energy levels (Champigny et al., 2020; Greenham et al., 2021). These findings highlight the importance of close follow-up, long-term monitoring, and the need for effective interventions for supporting both overt and more subtle physical challenges in the pediatric stroke population.

Parent-rated HRQoL of participants on dimensions of psychological well-being, moods and emotions, social support and peers, and school environment were comparable to norms. Despite these findings, a higher proportion of participants fell in the below average and extremely low ranges across all dimensions. The literature suggests variability in outcomes in these psychosocial domains. Our findings support the "disability paradox" (Albrecht & Devlieger, 1999), which suggests that patients may report high levels of well-being despite

experiencing significant impairments. This concept is explained by the patient's ability to adapt by adjusting their expectations (Caspar-Teuscher et al., 2019). We further propose that parents of children with medical histories tend to be more focused on visible physical challenges rather than psychological, emotional, and social difficulties, which are often less apparent. In addition, internalizing challenges may be influenced more by psychological adaptation and resilience than by objective measures of status.

Although age at stroke onset was not significantly associated with the HRQoL domains in our sample, exploratory findings suggest an emerging trend of a possible quadratic U-shaped relationship between age at stroke and physical well-being, psychological well-being, moods and emotions, and school environment, indicating that sustaining hemorrhagic stroke in middle childhood may be related to greater challenges in these domains. Middle childhood is a crucial period for substantial brain maturation, including the myelination of brain regions associated with motor control, reaction time, and executive function (Paris et al., 2023), making it highly vulnerable to neurological insults that occur during this developmental period. Despite this, the literature remains mixed, with some studies suggesting that older (Greenham et al., 2021) or earlier age at stroke (Ghotra et al., 2015; Neuner et al., 2011) predicts poorer outcomes, while others have reported no association (Kornfeld et al., 2017; O'Keeffe et al., 2017). Our findings add to the limited body of evidence, highlighting the need for further investigation into how developmental timing of stroke impacts HRQoL domains, particularly after childhood hemorrhagic stroke.

Our findings did not indicate any association between household income and HRQoL. This is notable given the well-established evidence of the impact of SES on neurodevelopmental outcomes in brain injury and stroke populations (Bartha-Doering et al., 2021; Champigny et al.,

2024; Venturini et al., 2024), as well as its influence on HRQoL in typically developing children (Le et al., 2023).

Lower FSIQ was significantly associated with lower scores in the social support and peer relationships domain, whereas higher GEC predicted worse HRQoL in all domains. Executive functioning also appears closely tied to real-world demands and quality of life. This is consistent with prior research suggesting that executive functioning skills play a pervasive role in shaping day-to-day functioning and well-being of pediatric patient populations (C. Murphy et al., 2021; Schraegle & Titus, 2016). Executive functioning challenges are highly prevalent and consistently reported in pediatric stroke literature, with notable difficulties in inhibition, cognitive flexibility, and working memory, even when other cognitive and intellectual abilities remain intact (Rivella & Viterbori, 2021). These challenges are associated with a wide range of difficulties, including academic, social, psychological, behavioural, and emotional challenges (Champigny et al., 2020; Everts et al., 2008; O'Keeffe et al., 2017). The observed association between FSIQ and social support and peer relationships may reflect the role of intelligence in navigating support and interpersonal relationships. The more consistent relationship between GEC and HRQoL domains underscores the need for incorporating executive functioning-focused interventions and accommodations in both clinical and educational settings to optimize the overall quality of life outcomes for pediatric stroke survivors. Furthermore, the above-discussed trends indicated lower parent-rated HRQoL scores in the domains of physical well-being, psychological well-being, mood and emotions, and school environment for children who experienced stroke during middle childhood specifically, a period coinciding with the maturation of brain regions related to executive functions. These potential U-shaped trends, along with our findings of significant associations between executive functioning abilities and all HRQoL domains, warrant future

investigations into the association between challenges in executive functioning, age, and HRQoL outcomes in this population.

Limitations

This study is one of the few to examine HRQoL and its predictors in a childhood hemorrhagic stroke population. Several limitations must be acknowledged. The small sample size impacts the statistical power to include multiple predictors within a single model and the generalizability of the findings. Furthermore, given the age of the inclusion criteria (i.e., many participants were under 8 years old) and the small sample size, we focused solely on parental ratings of HRQoL. In older patients, self-reports may have provided further insight. We are only able to present findings at a single time point, and participants varied in the time elapsed since stroke; tracking quality of life trajectories longitudinally would be informative. Due to these challenges and the rarity and diversity of childhood hemorrhagic stroke, it is essential to promote multicenter collaborations. Future larger and longitudinal studies could further explore the HRQoL outcomes in this population. In addition, SES was only explored through household income and our small sample was skewed toward families with higher income levels. The limited SES variability may have obscured differences in HRQoL domains. Finally, due to our small sample size, we did not explore clinical predictors such as neurological severity, hemorrhage volume, laterality, clinical post-stroke complications, and the impact of time since injury, despite the knowledge that these factors may impact the neurodevelopmental trajectory of the pediatric stroke population.

Conclusion

Physical well-being appears to be the most prominent challenge in terms of HRQoL in survivors of childhood hemorrhagic stroke, suggesting that motor limitations, fatigue, and

reduced physical participation may persist post-stroke, even when psychological and emotional, school, and social functioning remain relatively intact. Our results further contribute to understanding the predictors of HRQoL, highlighting the impact of executive functioning challenges on all HRQoL domains and the role of FSIQ in protecting social support and peer relationships. Findings underscore the importance of monitoring and assessing the physical well-being domain alongside psychosocial functioning, as part of routine follow-up. Interventions should aim to address not only overt physical limitations and emotional adjustment, but also the more subtle aspects of physical well-being following pediatric stroke. Additionally, it is essential to monitor executive functioning in this population and implement interventions specifically designed to address these challenges. Findings suggest associations between age at stroke, executive functioning skills, and HRQoL, and highlight the potential complex interplay of factors affecting HRQoL. Future research is needed to investigate these associations and identify children at the greatest risk of HRQoL challenges.

Chapter 6: General Discussion

Childhood stroke is an important cause of acquired brain injury and disability in children and youth (Fuentes et al., 2016), with the majority of survivors experiencing long-term neurological challenges (Beslow et al., 2010; Chowdhury et al., 2022). The incidence of childhood stroke ranges from 2 to 13 cases per 100,000 children each year (Askarova & Zhurkabayeva, 2024; Ferriero et al., 2019), with both ischemic and hemorrhagic strokes occurring at similar prevalence rates. The neurocognitive, academic, and quality of life sequelae after ischemic stroke have received relatively greater attention in the literature in recent years. However, there are very few studies investigating these outcomes after childhood hemorrhagic stroke (Ferriero et al., 2019). Emerging evidence suggests that a substantial proportion of survivors of childhood hemorrhagic stroke face neurological, cognitive, academic, and psychosocial challenges (Champigny et al., 2025; Chowdhury et al., 2022; L. K. Murphy et al., 2017; Yvon et al., 2018). Further, recent findings indicate a "grow into deficit" model, which suggests that as childhood stroke survivors continue to develop, neurocognitive challenges may appear long after the initial acute injury (Hebert et al., 2016). The evolving neurocognitive challenges can further disrupt academic progress, social participation, and emotional well-being, ultimately leading to a lower quality of life (Gordon, 2014). Despite awareness of these challenges, childhood hemorrhagic stroke remains understudied. An improved understanding of the neurocognitive, academic, and quality of life sequelae in this population, as well as the predictors of these outcomes, is warranted to establish a comprehensive understanding of the specific challenges faced by this population and to identify the children who are most at risk (Janas et al., 2023). This knowledge will help guide clinical practice in identifying areas for close follow-up assessments and tailoring interventions to address these challenges.

Overview of Studies

My doctoral research comprised three clinical studies aiming to (1) characterize the neurocognitive, academic, and health-related quality of life outcomes in survivors of childhood hemorrhagic stroke, and (2) clarify the role of factors previously identified in the scientific literature as possible predictors of intellectual, academic, and quality of life outcomes. The three studies were developed and conducted at the Hospital for Sick Children in Toronto, Canada.

Study 1 aimed to characterize the neurocognitive and academic outcomes in survivors of childhood hemorrhagic stroke and examined four clinical and demographic predictors previously identified in the literature: age at stroke, hemorrhage volume, hemorrhage laterality, and socioeconomic status as possible predictors of intellectual and academic outcome in this population. Neurocognitive and academic abilities were assessed in 24 patients with a history of childhood hemorrhagic stroke. Neurocognitive abilities assessed included verbal comprehension, perceptual reasoning, working memory, processing speed, full-scale IQ, cognitive flexibility, sustained visual attention, sustained auditory attention, and divided attention. Academic abilities assessed included word reading, mathematical calculations, and spelling. Statistical analyses included a series of one-sample *t*-tests to compare the sample's performance across intellectual, academic, attention, and executive functioning measures with the norms. A series of univariate linear regressions was conducted to determine the association between hemorrhage volume and each intellectual and academic variable. A series of Welch's *t*-tests was used to assess the impact of hemorrhage laterality. Due to the small sample size and the aim of assessing multiple predictors, descriptive comparisons were used for predictors with more than one coefficient (i.e., age at stroke, as a quadratic relationship was assumed, and hemorrhage volume, as it was categorized into three different sizes). For age at stroke, descriptive comparisons were made

using locally estimated scatterplot smoothing (LOESS), and for hemorrhage volume, descriptive comparisons were illustrated with visualized boxplots.

Study 2 aimed to describe and discuss the influence of three clinical predictors: hemorrhage laterality, hemorrhage volume, and age at stroke on neurocognitive outcomes in three cases (one female age 13, two males ages 15 and 17) with history of childhood hemorrhagic stroke with similar etiology (i.e., arteriovenous malformation) and hematoma location (i.e., broadly within the temporoparietal region). Neurocognitive abilities assessed included verbal comprehension, perceptual reasoning, working memory, processing speed, verbal fluency, expressive and receptive language, aspects of executive function (i.e., inhibition, switching, and set shifting), and learning and memory. The performances of the three cases on these measures were presented in standard scores and classified according to the American Academy of Clinical Neuropsychology's classification system (Guilmette et al., 2020).

Study 3 aimed to characterize the health-related quality of life (HRQoL) in survivors of childhood hemorrhagic stroke and examined four clinical and demographic predictors previously identified in the literature: age at stroke, socioeconomic status, intellectual abilities, and executive functioning abilities, as possible predictors of HRQoL domains in this population. The HRQoL was assessed in 24 patients with a history of childhood hemorrhagic stroke, using a proxy parent questionnaire, the KIDSCREEN-52 (Ravens-Sieberer et al., 2008). Five dimensions of HRQoL were selected for analysis, based on their theoretical relevance as defined by the International Classification of Functioning, Disability and Health (World Health Organization, 2001): physical well-being, psychological well-being, moods and emotions, social support and peers, and school environment. Statistical analyses included a series of one-sample *t*-tests to compare the sample's parent rating on the five HRQoL domains with the established norms. A

series of univariate linear regressions examined the relationships between HRQoL and the predictors: age at stroke, socioeconomic status, full-scale IQ, and parent-rated global executive functioning composite.

Summary of Results

Results from Study 1 identified that participants with history of childhood hemorrhagic stroke had lower mean scores on all neurocognitive and academic measures compared to the normative population. The findings also identified that a higher proportion of the sample scored in the extremely low range on these measures than expected in the general population. This was especially pronounced in measures of divided attention and mathematics. The exploratory findings of study 1 illustrated two emerging trends concerning predictors of intellectual and academic outcomes. First, the exploratory plotting revealed a non-linear U-shaped pattern between age at stroke and all intellectual indices, with the exception of working memory and the academic skills of word reading, spelling, and mathematical calculation. Based on patterns shown in LOESS plots, we observed U-shaped trends suggesting that worse outcomes across verbal comprehension, perceptual reasoning, processing speed, reading, and spelling occurred around age 5, with performance generally stabilizing from approximately age 10. On the measure of mathematics, we observed the worse outcome at around 12 years of age at stroke, with a sharp rise onward. Further, we observed a linear relationship between age at stroke and working memory, with a mild decline from early childhood onward. Second, we observed a trend toward lower medians and more variable academic performance across all academic measures of reading, mathematics, and spelling, as hemorrhage volume increases from small to medium. Household income was positively associated with higher comprehension, and maternal education

was positively associated with mathematical skills. There was no evidence of differences in intellectual and academic outcome measures based on hemorrhage laterality.

Results from Study 2 revealed variable verbal outcomes in the three cases, despite similar hemorrhage location and etiologies. Both Case 1 and Case 2 exhibited challenges in verbal learning, verbal memory, word retrieval, and word production. In contrast, Case 3 showed broadly preserved verbal abilities. This review further revealed the potential role of hemorrhage volume in neurocognitive sequelae of stroke survivors. Case 3, who had a small-sized hematoma, demonstrated broadly age-appropriate abilities, whereas Cases1 and 2, who had medium-sized hematomas, exhibited more challenges. The study did not reveal trends suggesting the impact of age at stroke on neurocognitive outcomes. Case 1, who had sustained stroke in adolescence (i.e., 13 years of age) and Case 2, who had sustained stroke in early childhood (i.e., 5 years of age), both experienced persistent challenges in some common aspects of language (i.e., word generation and word retrieval) as well as distinct challenges in other areas. Further, the relatively preserved neurocognitive abilities of Case 3 and the neurocognitive challenges of Case 1 suggest variable outcomes following stroke in adolescence. Finally, the results of this descriptive study suggest that all three cases experienced mild to moderate difficulties in tasks associated with executive functioning.

Results from Study 3 identified that participants with a history of childhood hemorrhagic stroke had lower than norm parent-rated HRQoL on the dimension of physical well-being, with no significant difference from the norms on dimensions of psychological well-being, moods and emotions, social support and peers, and school environment. Despite the overall average mean in most domains of HRQoL, a higher proportion of participants scored in the below-average and extremely low ranges than expected in a normally distributed group. In terms of predictors, age

at stroke and socioeconomic status (i.e., household income) were not found to be associated with any of the HRQoL domains. However, while age at stroke did not predict HRQoL, exploratory findings illustrate an emerging trend of a possible quadratic relationship between age at stroke and physical well-being, psychological well-being, moods and emotions, and school environment, suggesting possible vulnerability for lower HRQoL in these domains for children who sustained stroke in the middle childhood years and especially lower scores for those who had a stroke between 8 to 10 years. Lower full-scale IQ was associated with lower parent-rated HRQoL functioning in the domain of social support and peers. The overall parent-rated executive functioning was associated with lower parent-rated HRQoL across all five domains: physical well-being, psychological well-being, moods and emotions, social support and peers, and school environment.

The three studies of this dissertation are interconnected and collectively aim to provide a holistic understanding of outcomes following childhood hemorrhagic stroke. Each study builds on the previous one and seeks to address the ongoing calls of the literature for a multifaceted evaluation of outcomes (Greenham et al., 2016). The studies complement each other, as neurocognitive, academic, and quality of life impairments following stroke are closely interrelated.

Study 1 provided the basis for understanding of overall neurocognitive and academic trajectory in childhood hemorrhagic stroke population, by identifying the most commonly affected domains and examining key clinical and demographic predictors of intellectual and academic outcomes. The findings of this study reveal overall lower performance across various neurocognitive and academic measures, with potential interactions between multiple predictors, aligning with past research suggesting wide variability in neurocognitive outcomes post-injury

(Greenham et al., 2017). These findings informed hypotheses for the subsequent studies and highlighted a need to explore individual variability more deeply. As such, Study 2 built upon the foundation laid by Study 1 and employed a focused lens to examine the individual trajectories of three participants with similar etiology and hemorrhage location, to delve deeper into the broader trends identified in the larger sample of Study 1. Through detailed examination of their neurocognitive trajectories, Study 2 revealed the nuanced interplay of clinical, and perhaps unmeasured, predictors that contribute to the neurocognitive trajectory of childhood hemorrhagic stroke survivors, indicating no definitive predictor. Furthermore, the results of Study 2 indicated mild-to-moderate difficulties in tasks associated with executive functioning in all three cases, a finding that further underscored the importance of measuring executive functioning as a predictor of day-to-day functioning. Building on Studies 1 and 2, Study 3 provided a broader view of how children experience and adapt to life following hemorrhagic stroke and the impact of neurocognitive, clinical, and demographic predictors on the quality of life of the survivors.

Assessing HRQoL offers a more holistic view of the children's lived experience and their well-being in different domains (Ravens-Sieberer et al., 2008). Childhood survivors of stroke are at an increased risk of challenges with communication, academic advancement, emotion and behaviour regulation, and social participation (Abgottspon et al., 2022; Champigny et al., 2020; Deotto et al., 2019; Everts et al., 2008; O'Keeffe et al., 2017). By examining HRQoL outcomes in the same sample used in Studies 1 and 2, Study 3 allowed for a layered understanding of how functional impairments relate to perceived quality of life. Findings from Studies 1 and 2 illustrated challenges in various neurocognitive and academic domains in a sample of childhood survivors of hemorrhagic stroke. In contrast, Study 3 found that only physical well-being was lower in this sample, while psychological well-being, moods and emotions, social support and

peers, and the school environment were comparable to the norms. This suggests that sustaining hemorrhagic stroke in childhood may not predict lower HRQoL, echoing the concept of "disability paradox," wherein patients report relatively positive well-being in spite of objective impairments (Glymour et al., 2008). Amidst the overall resilience of the sample in terms of HRQoL, an examination of the predictors of outcomes in this study revealed significant insights regarding the impact of functional impairments on various HRQoL domains. Lower overall intelligence was associated with lower ratings in the social support and peer relationships domain, and more pronounced overall executive functioning challenges were associated with lower ratings across all five domains of HRQoL. These findings align with previous studies that have identified a reciprocal, bidirectional association between intellectual abilities and social support (Glymour et al., 2008), and neurocognitive abilities and psychosocial well-being (Knight & Baune, 2018; Max et al., 2002; Mukherjee et al., 2006).

The distinct yet interrelated approach of the three studies allowed for a thorough understanding of outcomes. Analyzing the same sample, the studies aimed to unravel the complex and multi-dimensional consequences of childhood non-traumatic hemorrhagic stroke. The studies vary in their methodology, starting with objective group-level analysis in Study 1, followed by objective individual-level insights in Study 2, and concluding with subjective group-level perspectives in Study 3, creating a comprehensive framework that encompasses both clinical insights and the lived experiences of survivors. The conclusions drawn from each study carry implications for clinical practice and future research directions. Collectively, the studies support a biopsychosocial model of recovery, emphasizing the importance of integrating various perspectives in outcome evaluation and intervention tailoring.

Clinical Implications

This dissertation yielded several clinically applicable findings related to assessment, conceptualization, and intervention planning for childhood survivors of hemorrhagic stroke that should be considered for practice by medical professionals working with this population.

First and foremost, the results highlight the neurocognitive and academic vulnerabilities of this population. Childhood survivors of hemorrhagic stroke may be at risk of challenges with verbal comprehension, overall intelligence, working memory, processing speed, cognitive flexibility, sustained visual attention, divided attention, reading, mathematics, and spelling. Among these, the most pronounced difficulties were observed in divided attention and mathematics, tasks that demand complex cognitive processes, including simultaneous engagement of working memory, attention shifting, and information processing speed, cognitive abilities particularly susceptible to disruption following early neurological insults (Anderson et al., 2002; Ballantyne et al., 2007). These findings challenge the previously held belief that pediatric hemorrhagic strokes are less likely to lead to severe neurological or neuropsychological impairments (Lo et al., 2008). Consequently, these findings should encourage clinicians and public health policy makers to establish systematic frameworks for the close monitoring of neurocognitive and academic development in this population. Furthermore, there is a need for the provision of early and tailored interventions within both clinical and educational settings. Although age at stroke was not found to have a statistically significant association with the outcomes, observed trends indicate that those experiencing hemorrhagic strokes during middle childhood may be at a higher risk for challenges related to intellectual functioning, academic performance, and health-related quality of life. Future research should aim to explore these trends further and replicate findings, as there is a need in clinical practice for information

regarding the nature and timing of support services for this population, in order to identify and support those who are most affected (Gordon, 2014). Timely neuropsychological assessments are essential as they enable early communication among medical professionals, families, and educational institutions, and foster advocacy for learning support and early allocation of resources for children in need.

All three studies yield important findings related to executive functioning vulnerabilities in this population. Study 1 revealed trends supporting the "growing into deficit" hypothesis (Westmacott et al., 2010), which suggests that executive functioning difficulties may become more noticeable as cognitive and academic demands increase. Study 2 revealed that challenges with executive functioning are evident even when other neurocognitive domains are intact. Furthermore, overall executive functioning abilities were identified as a key predictor of quality of life in Study 3. Collectively, these findings underscore the importance of the biopsychosocial framework in clinical practice and the necessity for recurrent and comprehensive assessments that extend beyond global cognitive indices to evaluate domain-specific functioning. Continuous follow-up assessments of executive functioning abilities are essential, even if challenges are not immediately evident following the injury and even when other intellectual and academic skills appear intact. A thorough approach to assessments enables clinicians to more effectively identify patterns of strengths and weaknesses, thereby supporting the tailoring of interventions and individualized support plans that address neurocognitive, academic, and quality of life needs.

Furthermore, Study 3 highlighted unmet needs regarding the lived experiences of this population, a domain often overlooked in standard neuropsychological assessments. Findings from this study revealed that children post-hemorrhagic stroke may face challenges with subtle aspects of physical well-being, a domain that traditional motor performance-based measures fail

to capture. As such, integration of HRQoL into neuropsychological assessments provides valuable insight into the lived experiences of this population. Findings should encourage clinicians to conduct in-depth interviews with youth and their families and use quality of life questionnaires to gain a more comprehensive understanding of recovery patterns and the day-to-day challenges faced by this population. The literature on outcomes in pediatric patient populations has increasingly highlighted the importance of considering the perspectives of children and their families regarding their well-being (Mason & Danby, 2011), as this subjective insight is crucial for developing interventions that are meaningful to children and their families (Jette & Haley, 2005; Msall, 2005).

Ultimately, the findings of the three studies in this dissertation have implications for psychoeducation and consultation with parents and educational settings. Clinicians can use this information to help families understand the potential long-term effects of childhood hemorrhagic stroke, promote realistic expectations, and collaborate on strategies to foster neurocognitive, academic, and quality of life functioning across various settings. These findings not only inform clinicians but also can assist in developing targeted accommodations and services within school-based support systems and educational policy frameworks.

Limitations and Future Directions

This dissertation has several limitations that must be acknowledged and addressed in future work. First, the small sample size for Studies 1 and 3 (n=24) represents a well-documented limitation in pediatric stroke research, particularly attributable to the rarity of pediatric stroke, especially childhood hemorrhagic stroke. This limitation constrained both the quantity and robustness of inferential analyses conducted, impacting the number of inferential analyses, reducing the statistical power to incorporate multiple predictors within a single model,

and limiting the generalizability of the findings from the univariate regressions. To ensure transparency, many of the analyses were presented as exploratory, focusing on providing preliminary data that highlights relevant trends and patterns of interest for future larger-scale studies. Further, due to the small sample size and a wider age range for inclusion criteria (i.e., including participants younger than 8 years old), we were unable to capture the HRQoL from the children's subjective perspective. Consequently, our analysis solely focused on parental ratings of HRQoL and did not incorporate self-reports from the children, which may have limited insights into the children's actual experiences and challenges. Large-scale studies are needed to replicate our results and assess the generalizability of these findings. Given the rarity and diversity of childhood hemorrhagic stroke, it is essential to engage in multi-centre international collaborations and long-term initiatives, to advance research in this field further.

Another limitation is the presentation of findings at a single time point, when participants varied in the time elapsed since their stroke. The variability in timing post-stroke may have introduced heterogeneity within the sample and hindered our ability to examine developmental changes over time. Neurocognitive challenges may become apparent several years after the injury, as environmental, cognitive, and academic demands increase consistent with the "growing into deficit" hypothesis (Westmacott et al., 2010), with some studies suggesting that impairments emerge in school age (Anderson et al., 2011; Levine et al., 2005; van Buuren et al., 2013; Westmacott et al., 2009). Thus, in order to fully understand the nuances in clinical presentation, it is essential to track the neurocognitive, academic, and quality of life trajectories of childhood hemorrhagic stroke survivors over time.

The predictors of outcomes examined in this dissertation were also limited, focusing primarily on a few clinical and demographic characteristics. For instance, in Studies 1 and 3, the

primary demographic characteristic evaluated was socioeconomic status. However, our sample displayed limited variability and skewed towards families with higher education and income levels, which may have obscured potential associations between socioeconomic status and various outcomes related to intellectual abilities, academic performance, and health-related quality of life. It is well established in the literature that socioeconomic status influences neurodevelopment, including in populations with brain injury and stroke (Bartha-Doering et al., 2021; Champigny et al., 2024; Venturini et al., 2024). In addition, other non-clinical predictors were not explored in any of the studies of this dissertation, despite the broader literature on pediatric acquired brain injury, suggesting the importance of various non-clinical factors in influencing outcomes, for instance, home environment and family functioning (Greenham et al., 2015; LeBlond et al., 2021; Semrud-Clikeman, 2010). Moreover, we did not examine psychosocial factors or clinical post-stroke complications, despite their known impact on the neurocognitive and academic trajectories of the pediatric stroke population (O'Keeffe & Cogley, 2021). Therefore, future research should investigate a wider array of clinical and non-clinical predictors with larger sample sizes to provide a more comprehensive understanding of recovery following childhood hemorrhagic stroke. In particular, understanding the predictors of neurocognitive outcomes is highly valuable for clinicians, as it enables them to refer patients to evidence-based neurorehabilitation services, tailored to their specific needs. Similarly, knowledge of predictors related to academic outcomes is essential for educational settings, allowing clinicians to make appropriate recommendations for tailored educational support. Lastly, awareness of factors affecting quality of life can help identify children at greater risk of facing daily challenges and guide the establishment of targeted interventions. Ultimately, future research on childhood hemorrhagic stroke should use a biopsychosocial framework to explore

the complex interactions of possible clinical and non-clinical factors affecting outcomes. Larger sample studies could utilize data-driven clustering approaches to uncover subgroups and examine differences in clinical and non-clinical variables.

Conclusion

Taken together, our findings suggest that childhood survivors of hemorrhagic stroke face challenges in various neurocognitive domains, academic functioning, and physical well-being. A closer examination of three cases with similar hemorrhage etiology and location revealed executive functioning challenges persist even when other domains remain relatively intact. In exploring predictors, trends suggested a U-shaped pattern between age at stroke and intellectual, academic, and HRQoL outcomes. Other clinical factors, including hemorrhage volume and laterality, were not found to be associated with intellectual and academic outcomes. Lower socioeconomic status was only associated with challenges in verbal comprehension and mathematics. The most significant finding was that lower executive functioning abilities negatively impacted HRQoL across multiple domains, underscoring the broad influence of executive functioning abilities on the daily lives of survivors of childhood hemorrhagic stroke. The overarching goal of this dissertation was to contribute to the advancement of research in developmental neuropsychology and to produce novel and clinically applicable findings regarding outcomes in childhood hemorrhagic stroke. A better understanding of the factors that predict outcomes and adjustments following a stroke is particularly valuable for neuropsychologists and clinicians involved in assessment, diagnosis, treatment, and referral. The findings of this dissertation should serve as a foundation for larger-scale studies in the future and guide clinical practices in developing services and interventions aimed at promoting optimal recovery for childhood survivors of hemorrhagic stroke.

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Note. The references below correspond to the references included in Chapters 1, 2, 3, 5, and 6.

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