

EXECUTIVE FUNCTIONING AND ITS RELATIONSHIP TO ACADEMIC AND SOCIAL-  
EMOTIONAL OUTCOMES IN CHILDREN WITH A HISTORY OF  
ARTERIAL ISCHEMIC STROKE

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## ABSTRACT

The extant research suggests that children with a history of stroke have deficits in executive functioning (EF). However, less is known about academic achievement and social-emotional functioning in this population and how EF impairment may contribute to outcomes in these domains. **Study 1** investigates EF and its relationship to academic achievement and social-emotional behavioural functioning in children with a history of unilateral arterial ischemic stroke. Thirty-two pediatric patients with stroke (mean age =  $9.5 \pm 2.7$  years) and 32 demographically equivalent, healthy controls were tested on standardized measures of working memory, arithmetic, and spelling. EF behaviour and social-emotional data were collected via standardized parent questionnaire. Relative to controls, stroke participants demonstrated significantly poorer functioning in metacognitive EF, behavioural-regulatory EF, working memory, math, and spelling. Highest rates of impairment were seen on the math tests. Regarding social-emotional outcomes, stroke participants displayed elevated conduct problems, aggression, and atypical behaviour relative to controls. Metacognitive EF was a significant predictor of academic skill, and behavioural regulatory EF was a significant predictor of social-emotional behavioral symptoms. Results suggest that executive deficits caused by pediatric ischemic brain injury can have cascading effects onto several important life skills and domains. Findings underscore the relative importance of early EF cognitive intervention in the pediatric stroke population. **Study 2** investigated the effects of age at stroke and lesion location on math, spelling, and reading academic outcomes using a large, retrospective sample of children with unilateral arterial ischemic stroke (mean age =  $10.9 \pm 4.0$  years). Children with combined stroke lesions demonstrated significantly poorer academic achievement in spelling relative to children who had stroke to cortical or subcortical regions alone. Furthermore, greater time since stroke

was associated with reduced academic achievement. Study 2 results provide important information on variables that modulate pediatric stroke outcome. Overall, the current project suggests that pediatric stroke patients with reduced EF capabilities and diffuse injury represent a group that is at increased risk of poorest neuropsychological outcomes. Furthermore, greater time since stroke is associated with progressive academic deficits. Findings assist with accurate prognosis and indicate need for early post-stroke cognitive intervention in affected youth. By elucidating domains of concern, the current research may help to direct and optimize therapeutic programs.

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## **Introduction**

Brain insult can result in significant cognitive deficits and in children it can impact school performance and reduce quality of life (Taylor & Alden, 1997). Despite this knowledge, youth who have experienced stroke have not been adequately studied. This is partially due to the popular misconception that stroke is exclusively a disease of late adulthood; however, developments in neuroimaging have indicated that stroke can occur at any age, including prenatal development (Kirton & DeVeber, 2009). The likelihood of experiencing early stroke is greatest within the first two years of life, but risk is still present throughout childhood with significant decline in incidence rates not occurring until adolescence (Matthews, 1994). Annually, a diagnosis of stroke is made 1 in every 2500-4000 live births, and yearly incidence rates have been found to range from 0.6 – 13 cases per 100,000 in youth aged one month to 18 years (Hartel, Schilling, Sperner, & Thyen, 2004; Kirton, Westmacott, & deVeber, 2007).

## **Mechanisms of Pediatric Stroke**

Stroke is defined as brain damage resulting from a disruption in the normal flow of blood in the brain (Festa, Lazar, & Marshall, 2008). Vascular disruption can be characterized by ischemia or hemorrhaging, and both of these broad stroke subtypes have been documented in youth. Ischemic stroke occurs when a blood-clot or narrowing artery causes a serious restriction of blood flow to a region of the brain (Kirton & DeVeber, 2009). The deprivation of blood denies brain tissue of essential oxygen and glucose and ultimately results in damage or death to surrounding neurons. Arterial ischemic stroke (AIS) comprises approximately 70% of all ischemic strokes in children and occurs when there is a blockage to one or more of the arteries supplying blood to the brain. Cerebral sinovenous thrombosis (CSVt) accounts for the remainder of childhood ischemic strokes and consists of brain damage caused by occlusion of

cerebral veins due to a blood clot or other blockage (Kirton et al., 2007). Two major mechanisms of ischemic stroke are thrombosis or embolus. Thrombosis occurs when a blood clot forms locally on a blood vessel and impedes or blocks the regular flow of blood. Embolism, however, is not due to a local process within the cerebral blood vessel. Instead, material that has formed elsewhere travels throughout the vascular system and lodges in a blood vessel downstream. Thus, an embolus is a detached, traveling intravascular mass (e.g. blood clot, tissue, cholesterol, or amniotic fluid) which detached from its point of origin and is carried by circulation. An embolus can become lodged in the arteries or capillary beds of the brain and cause obstruction or occlusion. (Festa et al., 2008). Most embolic strokes occur in the middle cerebral artery (MCA). In direct contrast, injury due to a hemorrhagic stroke is characterized by an excessive amount of blood (internal bleeding) resulting from the rupture of a weakened blood vessel. Blood accumulation compresses the surrounding brain tissue and excessive amounts of calcium present in the unwanted blood flow leads to neuronal cell death (Brier Cruz, 2001; Festa et al., 2008).

### **Initial Clinical Presentation in Pediatric Stroke**

In both ischemic and hemorrhagic stroke, the disruption in blood flow ultimately leads to permanent tissue damage, which is termed an “infarction”. Clinical presentation in pediatric stroke is dependent upon stroke mechanism and whether the stroke occurs perinatally (i.e., period before birth up to 28 days) or if it is childhood stroke (i.e., 29 days to 18 years). Symptomatic neonatal AIS or CVST typically presents as seizures within the first few days or weeks of life. However, 50% of ischemic perinatal strokes are “silent” (asymptomatic) and are only diagnosed retrospectively when motor asymmetry or early hand preference is noted by parents around four to six months. Such presumed perinatal ischemic stroke (PPIS) is then definitely diagnosed when subsequent magnetic resonance imaging (MRI) reveals an old arterial

infarction to the middle cerebral artery or periventricular white matter (Cardenas, Rho, & Kirton, 2011). Perinatal hemorrhagic stroke also frequently presents as seizures within the first few days or weeks after birth. Most cases, however, are diagnosed immediately during routine prenatal ultrasound and encephalopathy is readily apparent. Childhood stroke presentation tends to bear greater resemblance to adult stroke symptomatology. In childhood ischemic stroke, acute hemiparesis (weakness on one side of the body) and other focal motor deficits are common. Altered mental state, seizures, vertigo, lethargy, and dysphasia also commonly occur. An instantaneous, severe headache along with nausea or vomiting tends to be the hallmark presentation of childhood hemorrhagic stroke, and these symptoms have been documented in more than 50% of cases (Cardenas et al., 2011).

### **Risk Factors for Pediatric Stroke**

For reasons that are not well understood, there are a significantly greater proportion of males affected by pediatric stroke, and this is true for all stroke subtypes (Brier Cruz, 2001; Golomb, Fullerton, Nowak-Gottl, & deVeber, 2009). African American children also have a greater incidence, even after accounting for higher rates of sick cell disease (Cardenas et al., 2011). Risk factors for pediatric stroke are quite different from the common factors that contribute to stroke in adults, as lifestyle influences are rarely implicated. In children, the presence of congenital heart disease and hematological (blood) disorders greatly increase the risk of stroke (Brier Cruz, 2001; Cardenas et al., 2011; Festa et al., 2008). Additionally, almost half of all children with cerebral stroke infarction have signs of recent infection, with infection accounting for up to 40% of all pediatric CVST cases. Although the mechanism is not fully understood, head and neck infections, such as meningitis, sinusitis, and ear infection, are the most common cause of CVST in preschool children (Cardenas et al., 2011). Infections are

believed to result in stroke by means of the inflammatory response initiated by the immunity or when infection spreads to the endothelium, which are the cells that line the interior surface of blood vessels and lymphatic vessels (Pavlakis & Levinson, 2009). Arteriopathies (vascular anomalies) are also implicated as a main risk factor, and account for 50% of all pediatric AIS. Sickle cell disease greatly increases the risk of ischemia through blood clotting. Moyamoya disease and William's syndrome are two vascular diseases that result in narrowing blood vessels at the base of the brain and narrowing cerebral arteries, respectively. Small vessel disease increases the likelihood of thrombosis, embolus, and hemorrhaging. An association between mitral valve prolapse and pediatric stroke has also been found (Brier Cruz, 2001). In perinatal stroke, complex congenital heart disease and trauma present among the greatest risk factors. Maternal autoimmune disease, drug use, and preeclampsia are additional etiological factors (Cardenas et al., 2011).

### **Survival Rates and Pervasive Deficits**

Stroke survival rates in children are far greater than in the adult population, but differ markedly for the two subtypes, with hemorrhagic stroke being much more likely to cause acute death in children. When examined one month post stroke, there is an approximately 85-95% survival rate for ischemic stroke in youth, while 60%-80% of youth will survive a hemorrhagic stroke (Matthews, 1994). In comparing youth incidence rates, ischemic stroke has been found to be slightly more common (Brier Cruz, 2001). This pattern suggests that more children with the ischemic stroke subtype will live on to experience residual physical and cognitive problems as a result of their brain insult. In fact, it has been documented that more than half of pediatric AIS survivors will experience disabilities that are moderate to profound in severity (Kirton et al., 2007). In contrast, children with hemorrhagic stroke tend to possess better neurological outcomes

(Cardenas et al., 2011). The extant research suggests that youth with a history of ischemic stroke possess deficits in a wide variety of neuropsychological domains, including executive functioning, memory, visuospatial abilities, language, academic achievement, and intellectual abilities (Allman & Scott, 2013; Brier Cruz, 2001; Nass & Trauner, 2004; Westmacott, Askalan, MacGregor, Anderson, & Deveber, 2010).

Children who have experienced stroke are important to study because their etiology, symptoms, and prognosis are likely to show considerable difference from their adult counterparts (Brier Cruz, 2001), especially because brain injury is being sustained at a time of rapid brain development (Anderson, Catroppa, Morse, Haritou, & Rosenfeld, 2005). Unfortunately, the cognitive developmental trajectory for children with a history of stroke is currently unclear, and neuropsychological intervention programs are lacking, partly due to limited knowledge regarding areas of greatest cognitive decline and its relationship to age at brain injury and lesion location. Physiological motor deficits are a visible and thus well recognized area of impairment in this group of children, and the majority of intervention programs targeted for pediatric stroke involve physical and occupational therapies (Brier Cruz, 2001; Kirton et al., 2007). It is imperative that research and intervention efforts also focus on cognitive impairments, as there is evidence to suggest that such deficits could adversely impact youths' independence, academic achievement, psychological well-being, behaviour, and social interaction (Carlson & Wang, 2007; Clark, Prior, & Kinsella, 2002; Crick & Dodge, 1994). Hence, it is important to assess higher order cognitive abilities in children with stroke since it is likely that they are related to quality of life and functional outcome in a variety of domains.

Cognitive functioning following brain injury can depend upon several factors, including age at injury, time since injury, and lesion location (Max, Bruce, Keatley, & Delis, 2010; Taylor

& Alden, 1997). Stroke can occur in multiple regions of the brain and prior studies of lesion location and outcome following pediatric stroke have often divided ischemic infarction analysis into injury that has affected cortical, subcortical, or combined areas (e.g. Westmacott et al., 2010). Accordingly, in pediatric stroke the cortex of the brain can be damaged, sometimes in conjunction with the limbic system. Injury to these brain regions, particularly the frontal lobes of the cortex, is problematic since they have been known to support mental processes that are collectively known as executive functions (EF). Research suggests that EFs are highly important cognitive skills that contribute to adaptive functioning in other neuropsychological domains of ability, including social-emotional regulation and academic achievement (Max et al., 2010; Bernier, Carlson, & Whipple, 2010; Reynolds & Horton, 2008).

## **Neuropsychological Profile**

### **Executive functioning.**

EFs are higher order cognitive abilities that encompass goal directed actions that are adaptive to environmental demands (Reynolds & Horton, 2008). They include the abilities of problem solving, planning, alternating attention, inhibiting a prepotent response, monitoring personal performance, and controlling emotions. A multitude of brain imaging and lesion studies have established the frontal lobes, and in particular the prefrontal cortex, as the home of EF ability within the brain (Blakemore & Choudhury, 2006; Collins & Steinberg, 2006). EFs have a prolonged developmental course and significant gains in these abilities are made throughout childhood and into adolescence. The protracted course of EF development is believed to be directly related to maturation of the prefrontal cortex, which continues to myelinate and undergo synaptic pruning into early adulthood, and is also the last region of the brain to reach maturity (Blakemore & Choudhury, 2006; Reynolds & Horton, 2008). EF abilities may be particularly



vulnerable to impairment during childhood, when brain damage may disrupt the development of the immature frontal lobes (Max et al., 2010).

It is also important to note that the brain works together as an entire neurocognitive system, with various functions supporting one another. Of the entire cortex, the frontal lobes are the most highly interconnected region, and through complex circuits, the frontal lobes receive and transmit information to the posterior cortex, limbic structures, the thalamus, basal ganglia, brain stem, cerebellum and other subcortical regions (Cummings, 1993). For instance, the thalamus has been identified as a major source of incoming information to the prefrontal cortex, and lesions to the mediodorsal thalamic nucleus have been shown to impair EF working memory performance (Khan & Muly, 2011). In addition, emotional aspects of EF also depend upon subcortical regions, such as the limbic system, an area associated with emotion and long term memory (Cummings, 1993; Reynolds & Horton, 2008), and several PET and fMRI studies have found that that EF problem solving tasks, such as the Tower of London, activate both prefrontal and parietal cortices in their implementation (Carpenter, Just, & Reichle, 2000). In accordance with the previously mentioned observations, it is of no surprise that lesions to brain areas other than the prefrontal cortex have been found to relate to EF impairment (Long et al., 2011b; Reynolds & Horton, 2008). In fact, studies of EF behaviour subsequent to brain injury have indicated that frontal lobe functioning largely depends upon the integrity of both cortical-subcortical (cortico-strio-pallido-thalamic) and intercortical (frontotemporo-parieto-occipital) connections (Glozman, Levin, & Tupper, 2005).

These findings highlight the role of the prefrontal cortex and its interactions with cortical and subcortical brain regions in the neural networks underlying EF ability. EFs are likely to be even more broadly distributed and vulnerable in the brains of youth due to reduced functional

specificity and organization of brain structures (Anderson, Spencer-Smith, & Wood, 2011).

Accordingly, there is strong potential for EF impairment in children with a history of stroke since there are multiple locations in which infarction (permanent brain tissue damage) may disrupt neural circuits involved in the execution of EF (Reynolds & Horton, 2008). It is therefore of great importance to evaluate multiple domains of EF in this population and empirically determine the effects of executive dysfunction on other important cognitive domains, as there are other, more complex, neuropsychological abilities which are strongly dependent upon these basic skills. In particular, executive dysfunction may adversely impact one's social cognitive thought processes and the execution of academic skills. For instance, inhibition and emotional control are particularly relevant to social-emotional outcomes, while working memory is required for efficiently carrying out math operations (Bernier et al., 2008; Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Riggs et al., 2006).

The majority of the pediatric stroke research studies that have focused on EF outcome have utilized a standardized laboratory task paradigm in order to assess affected domains of cognition. A study by Max and colleagues (2010) implemented three standardized EF tasks; namely the Design Fluency Test, Wisconsin Card Sorting Task, and the Multilingual Aphasia Examination Controlled Oral Word Association (COWA). The study compared the EF performance of two separate pediatric stroke groups, divided according to age at stroke, to the EF performance of orthopedic controls. Children who had experienced stroke in childhood (average age at stroke was 7.8 years) had substantially lower scores on the Design Fluency test, which represents the EFs of cognitive flexibility, working memory, and initiation. The childhood stroke group also had lower scores on the COWA phonemic fluency test, which taps into initiation and simultaneous processing. When the group of children who had experienced infant

or prenatal stroke (i.e. before 12 months) were compared to orthopedic controls they had slightly poorer performance on the Wisconsin Card Sorting Task, which is a measure that assesses cognitive set-shifting, planning, and inhibition. This research suggests that children with a history of stroke experience trouble with several core EF abilities. It also suggests that EF outcome is non-linear and depends upon the stage of neurocognitive development in which the stroke was incurred (Max et al., 2010). Different EFs may have different periods of peak vulnerability, and this is likely dependent upon the developmental trajectory of individual EF skills in childhood. For instance, EF abilities which naturally emerge during middle-childhood years will be most vulnerable to stroke related brain injury during this time. The findings by Max et al. (2010) imply that cognitive flexibility, working memory, and initiation are more strongly impacted by childhood stroke, while shifting, planning, and inhibition are slightly more vulnerable to stroke during infancy.

Other standardized laboratory task based studies have selectively examined the EF of working memory, which namely is the ability to hold information in mind while concurrently engaging in additional mental processes. Together, results suggest that children with a history of stroke are also vulnerable to working memory deficits (Allman & Scott, 2013; Westmacott et al., 2010; White, Salorio, Schatz, & DeBaun, 2000). According to an influential and empirically supported cognitive model proposed by Baddeley and Hitch (1974), working memory consists of a central executive that subsumes two core slave systems; these are the phonological loop and the visuospatial sketchpad. The phonological loop is the part of working memory that is responsible for storing and processing sound or phonological information, whereas the visuospatial sketchpad stores and processes information that is in visual or spatial form. For instance, the phonological loop is activated when rehearsing and retrieving a phone number from

memory, while the visuospatial sketchpad is activated during personal navigation when attempting to recall a route. The central executive monitors and coordinates the activities of the slave systems and is the most important component of the model. The central executive directs attention to each of the specialized storage systems and enables working memory to selectively attend to some visual or auditory information, while ignoring others (Baddeley & Hitch, 1974).

The capacity and functioning of the central executive is typically assessed by complex tasks where participants are required to simultaneously store and process information. For instance, a classic and widely recognized test of the central executive is “backward digit recall”, where an individual must recall a string of digits and recite them in reverse order. This is a verbal test of working memory, and tests the verbal central executive (Alloway et al., 2004). In contrast, other tests have a visuospatial component and load more heavily onto the non-verbal central executive. While more stroke research studies have implemented these tasks in adult populations, emerging research has also examined working memory capacity in children with a history of stroke by using tests that tap into the verbal central executive and phonological loop. The extant pediatric stroke literature documents subtle deficits to these core cognitive skills. Westmacott and colleagues found that poorest verbal central executive outcomes were associated with neonatal stroke and that deficits tended to emerge during the school years (Westmacott et al, 2010; Westmacott, MacGregor, Askalan, & deVeber, 2009). Other research supports a non-linear trend, where children who had stroke in early infancy or late childhood had similar verbal central executive scores that were significantly lower than the normative population (Allman & Scott, 2013). Other research administered a word span task that selectively tapped into the phonological loop component of working memory. The study reported dysfunction to the phonological loop in children with anterior stroke infarcts, with poorest performance observed in children who had

diffuse stroke infarcts. Children who had posterior infarcts demonstrated a preserved working memory profile (White et al., 2000).

Together, results suggest that there is reduced verbal working memory capacity in children with a history of stroke (Allman & Scott, 2013; Westmacott et al., 2010; Westmacott et al., 2009; White, et al., 2000). These studies also identify lesion location and age at stroke as relevant variables in determining working memory functioning, since they are likely to modulate outcome (Westmacott et al., 2009; White, et al., 2000). Further research is required to determine the effects of pediatric stroke on the non-verbal central executive, as there is lack of research implementing tests of visuospatial working memory ability in this population.

Children with stroke represent a heterogeneous group, and considerable variation in functioning has been observed, ranging from extreme cognitive impairment to average or even above average abilities (Funnell & Pitchford, 2010). Thus, it is important to identify moderating variables when predicting cognitive outcome after childhood stroke. In addition to age at stroke, lesion location and lesion size have been recognized as important moderating factors in EF ability (Long et al., 2011a, 2011b). Large lesions that occupy a considerable portion of brain volume appear to be connected to poorest outcomes. For instance, in a research study by Long et al. (2011a), pediatric stroke patients significantly differed from the normative population in the EF domains of attentional control, cognitive flexibility, and information processing. The overall mean scores in each category were within the low-average range of performance for the stroke group. In addition, 40 to 70% of the stroke participants had impaired performance (scores greater than two thirds of a standard deviation below the mean) in the EF domains of sustained attention, inhibitory control, working memory, mental flexibility, and divided attention. Despite the large number of low scores, the researchers observed considerable range in performance that spanned

from two standard deviations below to two standard deviations above the test mean. Lesion size significantly accounted for the poor performance of many stroke patients, with larger lesions proving to be the most detrimental. Large lesions were operationalized as infarctions that were greater than 25% brain volume (Long et al., 2011a).

Another study by Long and colleagues (2011b) examined the effects of lesion location on EF ability. Analyses revealed that lesions involving frontal or extra-frontal regions of the brain generally impact equally on EF performance. Stroke lesions in both locations were associated with reduced performance in both “cool” (metacognitive, problem solving) and “hot” (emotional, motivational, inhibitory) aspects of EF. When the frontal and extra-frontal lesion groups were directly compared, frontal stroke was associated with poorer everyday EF outcomes involving emotional control and planning /organization, while the extra-frontal lesion participants fared worse on goal setting and cognitive flexibility. Subcortical stroke also adversely affected EF, but mainly produced trouble with everyday executive skills involving social and emotional EF regulation (Long et al., 2011b). Lesion laterality impacted equally, as there were no significant differences in hot or cool EF abilities between children who had incurred left or right hemispheric stroke. Results indicate that the integrity of the entire cortex is important for the normal development of executive skills. Moreover, specific EF skills may be more dependent upon intercortical and cortical-subcortical connections; this study identified goal setting, cognitive flexibility/shifting, and behavioural social-emotional EFs as being strongly impacted by stroke in areas outside of the frontal lobes.

To date, only two pediatric stroke studies have utilized a standardized questionnaire measure of EF ability. Such measures are valuable since they can quickly and concisely gather information on a child’s functioning across multiple pertinent EF abilities. For instance, the

Behavior Rating Inventory of Executive Functioning (BRIEF; Gioia, Isquith, Guy, & Kenworthy, 2000a) is a reliable and valid measure of a child's EF capabilities as they pertain to daily behaviours and real life functioning. This parent and teacher rated questionnaire possesses greater ecological validity and comprehensiveness than laboratory tasks and can be very helpful in assessing the “hot,” behavioral and social-emotional components of EF regulation in children (Gioia, Isquith, Guy, & Kenworthy, 2000b). When parent and teacher forms of the BRIEF were administered to collect information on the everyday EF functioning of childhood stroke patients, scores were elevated on the Behavioral Regulation and Metacognition Indices as well as the Global Executive Composite (Long et al., 2011a, 2011b). On the BRIEF, higher scores are representative of poorer functioning. Hence, results were indicative of executive dysfunction in several daily EF abilities. The Behavioral Regulation Index reflects a child's ability to perform cognitive set shifting and modulate emotions and behaviour through inhibitory control. The Metacognition Index reflects a child's capacity to problem solve, self-manage, and monitor personal performance on daily tasks (Isquith, Gioia, & PARR Staff, 2008). Further research utilizing EF questionnaires will help to verify the types of everyday tasks that youth with stroke are experiencing trouble with.

#### **Academic ability and social-emotional functioning.**

Executive functioning consists of multiple domains and, unfortunately, little is known about the full extent of EF impairment in children with stroke and how it relates to important everyday outcomes. The deficits observed in the previously reviewed studies are concerning, given that EFs are known to subserve other cognitive functions of greater complexity; thus, deficits to EFs may have cascading effects upon other cognitive and behavioural domains (Bernier et al., 2010). EF abilities are termed “executive” because they are believed to play a

supervisory role in human cognition, including high level processing of complex information and integration of information stored throughout the brain (Shallice, 2004). As a result, EF can affect processing within the domains of learning, memory, language, and visual perception (Luria, 1966; Miyake, Friedman, Rettinger, Shah, Hegarty, 2001).

Notably, research in healthy children has shown strong connections between EF ability and academic achievement in both arithmetic and literacy (Bernier et al., 2010; Blair & Razza, 2007). For instance, Geary and colleagues found that working memory was strongly predictive of proficiency with arithmetic tasks in 6 to 7 year old children (Geary et al., 2007). It has also been well established that children with math learning disability do not perform well on tasks of working memory when compared to typically achieving children of the same age and grade level (Geary, Hoard, Byrd-Craven, & Desoto, 2004). Research suggests that EF also plays a vital role in the social-emotional development of children, including the development of social competence, which encompasses the degree of appropriateness and effectiveness in social interactions with other individuals (Crick & Dodge, 1994; Riggs, Jahromi, Razza, Dillworth-Bart, & Mueller, 2006). Specifically, the EFs of emotional control, inhibition, and problem solving have been recognized as making important contributions to the ways in which children and adults interact with others, although much of this knowledge is seemingly intuitive. In order to be effective in social situations we must be capable of modulating our emotional responses, resisting impulses, and problem solving through dilemmas (Riggs et al., 2006).

There is a small quantity of recent literature concerning the social-emotional profile of children who have experienced stroke, but early studies suggest that neonatal stroke has an adverse impact on emotional expression, comprehension, and social skills throughout childhood (Hartel et al., 2004). According to an older study which administered a measure of child



personality via parental report, children with a history of ischemic or hemorrhagic perinatal stroke present with increased behavioural problems when compared to healthy children of the same age. Abnormal scores on adjustment, social competence, and emotional behaviour were particularly apparent. Low scores on these scales are indicative of poor social relations, low self-esteem, isolation, and peer rejection. Issues with discipline and self-control were also noted (i.e. impulsivity, anger, poor school behaviour). In regards to lesion location, the study found that any focal brain injury of early onset predisposes children with stroke to a variety of cognitive and behavioural difficulties (Trauner, Panyard-Davis, & Ballantyne, 1996). Another study examined long term functional outcomes of pediatric stroke survivors and found reduced adaptive daily functioning in the domains of communication and socialization of the Vineland Adaptive Behaviour Scales (VABS). The socialization domain represents degree of facility with interpersonal relationships and various coping skills, while the communication domain represents the child's receptive, expressive, and written communication skills. Both scores were in the moderately low range for survivors of pediatric stroke. Moreover, lower scores in communication and socialization were predictive of reduced life satisfaction. This relationship underscores the importance of social outcomes in the adaptive daily functioning of these children (Hurvitz, Warschausky, Berg, & Tsai, 2004).

The findings of Hurvitz and colleagues (2004) converge with another recent study, which also found moderate levels of social-emotional difficulty. In this study, elevated rates of peer problems and reduced prosocial tendencies were discovered in a childhood stroke group, as indicated by teacher ratings on the Strengths and Difficulties Questionnaire (Gomes, Spencer-Smith, Jacobs, Coleman, & Anderson, 2012). However, these problems were considered to be of moderate impairment in the stroke group when compared to impairment rates seen in a healthy

normative comparison population and in a group of children who had prenatally experienced malformations of cortical development (MCD). Hence, children with a history of stroke display reduced social competency, but these problems may not be as severe as what would be found in other pediatric brain injury populations (Gomes et al., 2012). This study also measured executive processes of attention and found that children with stroke demonstrated a reduced capacity to shift focus and had higher rates of impairment in this domain than what would be expected in a normative comparison group. Importantly, significant correlations existed between attention shifting and social competency, where lower performance on Shifting Attention was associated with lower ratings on the Peer Relations scale and higher ratings on the Peer Problems scale (Gomes et al., 2012). Results appear to confirm a relationship between executive processes and social-behavioural skills, where executive deficits caused by brain injury can have cascading effects onto several important life skills and domains. Further research is necessary to uncover the full range of social-emotional tendencies in children with stroke and how they are impacted by executive abilities.

While pediatric stroke has been known to result in verbal language impairment, especially at a younger age of onset (Chapman, Max, Gamino, McGlothlin, & Cliff, 2003), less is known about academic achievement in these children. To date, only a handful of studies have examined scholastic abilities in this population, and some of this research possesses inherent limitations. In addition to examining EF outcome, the previously described Max et al. study (2010) also examined the impact of age at stroke on academic achievement by administering the math, reading, and spelling subtests of the Wide-Range Achievement Test – Revised (WRAT-R). The researchers, again, examined youth who had suffered early stroke (i.e. before 12 months) and youth who had experienced stroke in childhood (average age at stroke was 7.8 years). Stroke

participants performed poorly in all three academic areas in comparison to orthopedic controls. Unfortunately, the authors did not test for statistical differences in academic performance between the stroke and control groups due to the small size of the participant samples; however, the study did report effect size measurements. Notably, children with early stroke fared much worse in their reading, spelling, and arithmetic academic achievement scores in comparison to orthopedic controls. This was particularly true for reading and spelling, as evidenced by large mean difference scores and effect sizes of medium strength in these academic domains. Differences were not as large for youth with childhood stroke (Max et al., 2010).

Early vulnerability of academic skills was also supported by a Brazilian school study which found a positive relationship between early cortical hemorrhaging or ischemia and weaker performance on school tests of spelling, reading, and arithmetic (das Dores Rodrigues et al., 2011). Math, spelling, and reading scores were all significantly lower in the stroke group, with many children performing in the impaired range, especially on the arithmetic task. This was in comparison to healthy control children who did not have a history of stroke. Unfortunately, little information is available on the nature of the academic achievement scale used in this study (i.e., format, standardization), as it was unique to the Brazilian school system and has not been utilized elsewhere (das Dores Rodrigues et al., 2011).

Another study, focusing exclusively on reading and writing, detected delays in both of these skills, with particular difficulty in written expression (Sanders, Gentry, & Davis, 1997). Children with stroke were observed to produce incomplete, run-on sentences with incorrect grammar and punctuation. Vocabulary development was spared however, and no significant problems were detected in this domain. It is important to note that the participant sample consisted of children who had sustained stroke due to a blood disorder (sickle cell disease). The

children in this study may differ from other children with a history of stroke in several respects, making it difficult to know whether the obtained results can be generalized to all pediatric stroke cases. For instance, individuals with sickle cell disease have increased risk of anemia, reduced blood oxygen levels, and children have been noted to have a greater number of school absences due to painful sickle cell crises (Malowany & Butany, 2012; Sanders et al., 1997). Accordingly, there may be additional factors contributing to the observed pattern of academic difficulty in this group of youth.

Despite clear evidence for early academic vulnerability provided in previous stroke studies, Allman and Scott (2013) decided to examine age at stroke effects more closely by dividing unilateral ischemic stroke patients into three groups based on the age at which they incurred stroke during youth. This research supports a *non-linear model* of academic outcomes and indicates a possible protective effect for strokes occurring mid-childhood. Specifically, stroke in infancy (<12 months) or late childhood (between ages 6-16) resulted in poor outcomes for spelling and working memory. In contrast, childhood stroke between the ages of one to six resulted in a relatively preserved neurocognitive profile: children in this group were not significantly different from normative values in their reading, spelling, or working memory scores. Unfortunately, these researchers did not administer a test of arithmetic (Allman & Scott, 2013).

The results from the previously described Brazilian study (das Dores Rodrigues et al., 2011) converge with other research on pediatric neurological disorders, which frequently cite greater impairment in the area of arithmetic, as mathematical competency is a complex ability which often draws upon various brain regions and basic cognitive skills that can be adversely impacted by brain lesions (e.g. Barnes, Fletcher, & Ewing Cobbs, 2007; Taylor, Epsy, &

Anderson, 2009; Till et al., 2011). For instance, the execution of a math problem often requires working memory for numerical information, such as when one is carrying over during addition (Geary et al., 2004; Geary et al., 2007). One must also inhibit inappropriate responses and shift between different problem solving styles, thus requiring the EFs of inhibition and cognitive flexibility. Visuospatial awareness of the number line is also essential for math problem solving and working with integers (Bachot, Gevers, Fias, & Roeyers, 2005; Geary et al., 2007). Both visuospatial and working memory deficits have been documented in youth with stroke history, along with other essential EF deficits (Akshoomoff, Feroletto, Doyle, & Stiles, 2002; Schatz, Craft, Koby, & DeBaun, 2004; Westmacott et al., 2010), thereby increasing the potential for arithmetic difficulties. While reading and spelling also require various cognitive skills, difficulties in these academic domains in children with stroke may be related to more localized injury in the brain, as left hemisphere temporal and frontal lobe structures have long been associated with language, even early in development (Krashen, 1973). For instance, Funnell and Pichford (2010) have linked reading disorder and impaired verbal IQ to left hemisphere pediatric stroke infarctions.

The available research literature suggests that academic achievement suffers in pediatric stroke, especially at an early age of brain infarct. There is need for more research in this area in order to definitively determine the types of academic achievement that are most impaired and the effect of age at stroke on psycho-educational developmental trajectory. Such information will elucidate whether a linear or non-linear age related trend truly exists, thereby increasing prognostic knowledge concerning important school outcomes. In addition, it may also support the effective targeting of academic abilities in remedial intervention programs. To this end, research should also empirically address the effects of cortical, subcortical, and combined lesion

locations- To date, it is believed that larger lesion size and diffuse damage is associated with poorer cognitive outcomes, which is a finding supported by Westmacott et al. (2010) in a regional brain analysis of children who had experienced ischemic stroke.

In light of the probable contribution of EFs to academic and social functioning, all three outcomes reflect essential areas of investigation in children with stroke, especially since the extant research literature suggests executive dysfunction across several domains. Executive dysfunction in this group of children may negatively impact scholastic performance and social-emotional competency with peers, resulting in a failure to meet several developmental milestones and a reduction in quality of life. The remaining questions and limitations in the preceding pediatric stroke research warrant greater study of these important outcomes and their relationship to EF. If deficits are strongly related to EF capabilities, then this will be an impetus for the development of early cognitive EF intervention.

### **The effects of early injury: Vulnerability versus plasticity.**

Brain development is an extended process that takes place throughout childhood, adolescence and beyond, and the immaturity of the young developing brain makes children with a history of stroke an important group to study. The effects of early versus late brain damage upon cognition have been heavily debated, but for many years plasticity theory (also known as the “Kennard principle”) represented a dominant theoretical perspective within neuropsychology. According to this view, deficits are milder and recovery is quicker when brain damage occurs in childhood as opposed to adulthood (Brier Cruz, 2001). It was argued that this is because the brain is plastic and changeable in early life and therefore able to adapt to damage by forming new neural connections. Consistent with this perspective, the young brain would essentially be able to “re-organize” itself, and unharmed brain areas could compensate for the functions

previously performed by damaged regions. Plasticity theory was derived from Kennard's early studies on the motor system in animals and from studies on language functioning after localized injury to the left cerebral hemisphere (Finger, Buckner, & Buckingham, 2003; Kennard, 1936; Vargha-Khadem, O'Gorman & Watters, 1985).

However, recent research into the lasting effects of traumatic brain injury during childhood (Anderson et al., 2005; Taylor & Alden, 1997) has garnered increased support for a vulnerability theory. In direct contrast to the Kennard principle, vulnerability theory posits that early injury will produce greater deficits since childhood encompasses a period of time in which the brain is still in a rapid state of growth and development, as neural networks are still maturing and the frontal lobes are continually undergoing myelination. Early injury is thought to interfere with this sensitive period in brain development and impede the acquisition of developmentally appropriate cognition. Several neuropsychological explanations have been proposed to account for observed patterns of vulnerability following early brain damage. For instance, it has been argued that earlier injuries disrupt the normal migratory pattern of neurons and thereby lead to poorer outcomes (Hicks, D'Amato, & Glover, 1984). There is also indication that early brain damage has implications for neuronal repair, where anomalous neural reconnections are likely to form during infancy and childhood. This is largely attributed to the fact that axonal weeding is still occurring in brains of youth and injury can cause the retaining of neurons that would normally have been destroyed (Max et al., 2010). Finally, early injury is believed to interfere with the normative developmental course of myelination in the brain, especially in the frontal lobes, thereby resulting in white matter abnormalities (Max, 2004).

In accordance with vulnerability theory, the protracted course of EF development and slow maturation of the frontal lobes may make these abilities particularly vulnerable to

disruption during youth. This may have cascading effects onto other cognitive domains and life skills because EFs play a supervisory role in human cognition. Findings from studies on age related differences in cognitive outcome following pediatric stroke largely support a vulnerability view, and stroke during prenatal development and infancy is especially linked to poorer cognitive outcomes (Max et al., 2010; Westmacott et al., 2010). As previously discussed, Max and associates (2010) compared children with late stroke (average age at stroke  $7.8 \pm 3.2$  years) to children who had experienced stroke before 12 months of age on a variety of neuropsychological measures. The group of children who had experienced stroke very early in their development had significantly lower scores on tests assessing a wide variety of neurocognitive domains, including visuospatial skills, language, memory, and the Wisconsin Card Sorting Task which is a measure that taps into the EFs of cognitive set-shifting, planning, and inhibition. However, there were two standardized clinical laboratory tests of EF ability that showed the opposite pattern, with the late onset stroke group demonstrating greater impairment. This result occurred for the Design Fluency test which represents the EFs of cognitive flexibility, working memory, and constructional abilities, and for the test of phonemic fluency which represents the EFs of initiation and simultaneous processing.

Results from the Max et al. (2010) study suggest a non-linear trend between EF impairment and age at brain injury. Findings were not consistent and depended upon the EF subdomain in question. By extension, it is unlikely that all neurocognitive abilities (e.g. academic achievement subjects, memory subtypes, visuospatial skills) will possess a uniform developmental trajectory and period of peak vulnerability. Although perinatal and infant brain injury carries greater cognitive repercussions, there may be select abilities that do not share this pattern. Therefore, global cognitive impairment in early stroke is unlikely. A study by



Westmacott and associates (2010) also found that neuropsychological test performance depended upon the cognitive domain in question and the age at which stroke was experienced during youth. Overall, earlier age at injury was indicative of greater cognitive impairment; however, the relationship between cognitive outcome and age at stroke was modulated by lesion location. Subcortical stroke lesions in the basal ganglia or thalamus during the perinatal period were found to be particularly detrimental to future cognitive outcome. When compared to children with late stroke affecting the same subcortical regions, the perinatal stroke group performed more poorly on a variety of measures, including overall intellectual functioning and working memory. Conversely, the peak vulnerability period for children who had sustained cortical lesions was one month to five years at age of stroke, and this result applied to perceptual reasoning and overall intellectual performance (Westmacott et al., 2010).

The effect of age at stroke on academic achievement remains an important area of investigation. A prevailing question concerns whether or not the left and right hemispheres of the brain both have the capacity to develop language (Funnell & Pichford, 2010). Those who adhere to plasticity theory have asserted that children with left hemisphere stroke do not suffer the verbal and reading deficits seen in adults with the same injuries due to the capacity for functional reorganization in the young developing brain. A model has been proposed where the right hemisphere can compensate by taking over language functions that were previously performed by the damaged left hemisphere region (Finger et al., 2003). However, in their investigation of these claims, Funnell and Pichford (2010) did not find evidence for a compensatory model in children with unilateral stroke. A broad range of functioning was observed in children with left hemisphere stroke, but the majority of these participants attained below average standard scores. Many left hemisphere stroke participants were impaired in single word reading accuracy,

spelling, and reading comprehension, with some performing as poorly as 4 standard deviations below the mean (Funnell & Pichford, 2010).

Recent research suggests a protective effect for mid-childhood stroke. Allman and Scott (2013) published a comprehensive research study reviewing the effects of age at stroke on various neurocognitive abilities during youth. Included were three groups of stroke patients, categorized according to age at stroke. In addition to EFs, memory, and other domains of cognition, the academic abilities of spelling and reading were examined using Wechsler scales and the scores of the three stroke groups were compared to published population norms. Overall, poorest outcomes were observed in children who sustained stroke very early or late in their youth development (i.e., before 12 months or between the ages of 6-16). In contrast, children who experienced their stroke between 1 to 6 years tended to present with a normative neurocognitive profile across measures. It has been suggested that the nonlinear relationship between age at stroke and later academic and cognitive outcomes are due to the processes of plasticity and neurological vulnerability. In comparison to older youth, youth in early childhood have greater potential for cortical reorganization following stroke. While plasticity is also high in the infant brain, its immature and underdeveloped state also confers vulnerability when injury occurs. The potential for reorganization is not fully realized in the infant brain due to rapid neural changes and reduced functional specificity at this stage of brain development (Allman & Scott, 2013; Everts et al., 2008; Westmacott et al., 2010). Accordingly, the vulnerability of the infant brain and the developed, less-plastic nature of the older childhood brain may make these groups more susceptible to academic and EF difficulties, whereas stroke between the ages of 1-6 may lead to a preserved neurocognitive profile.

A longitudinal study has provided further support for the vulnerability of academic

abilities when stroke occurs during very early development, around the time of birth. However, this research also provides insight into the stability of deficits over time (Ballantyne, Spilkin, Hesselink, & Trauner, 2008). Children with a history of ischemic perinatal stroke were found to have significantly poorer performance on the reading, spelling, and math subtests of the WRAT when compared to a healthy demographically matched control group. When normed standard scores were re-examined after a 3 year test-retest interval it was found that the academic performance of both groups remained stable over time. Hence, even though children with early stroke demonstrate academic difficulties, this group does not experience a decline in age-relative math, spelling, or reading abilities over the school years (Ballantyne et al., 2008). This represents an important finding, as time since injury analyses often reveal deficits that are later appearing and cumulative, where children fail to meet developmental milestones as they age (Dennis, 2000). Ballantyne's results are promising for scholastic remediation efforts, and further studies should substantiate whether this result also holds for youth who sustained stroke in different stages of childhood.

Collectively, the results concerning age related differences in this population are concerning, as they signify that children with stroke represent a group that is especially in need of early cognitive intervention. Perinatal and infant stroke appear to bear the poorest outcomes; however, specific cognitive abilities may have peak periods of vulnerability during late childhood. In addition, the brain may be less capable of functional reorganization and compensation after injury in early and late childhood. Children with a history of stroke are in need of cognitive remediation specifically tailored to their profile of impairment, and further investigation into the relationship between age at stroke and cognitive outcome will aid in this endeavor. It would appear that the earlier the intervention is implemented, the greater its efficacy

in remediating impairment and potentially restoring a normal cognitive trajectory. The effects of early versus late stroke on academic achievement represents an especially relevant area of research, as academic abilities constitute important life skills that are linked to life satisfaction, adaptive daily functioning, and future occupational success.

### **Project Objectives**

The overarching goal of the current project was threefold. Firstly, we sought to expand upon the current EF pediatric stroke literature by evaluating a broader range of EF abilities. By administering standardized laboratory working memory tasks and a questionnaire that assesses both metacognitive and behavioural regulatory EF abilities, we attempted to gain greater insight into the domains of EF impacted by pediatric stroke. Secondly, we wanted to examine if EF deficits in this population impact on academic achievement and social-emotional behavioural functioning. These outcome variables were examined because existing research literature suggests that there are subtle deficits in spelling, math, reading, and social functioning in children with a history of stroke (Gomes et al., 2012; Max et al., 2010). Furthermore, connections between these important outcomes and EF have been established in healthy children (Alloway, Gathercole, Kirkwood, & Elliott, 2009; Geary et al., 2007). Thirdly, we wanted to study the effects of age at stroke and lesion location on academic outcome, as these variables may be important modifiers in pediatric stroke outcome. Study 1 was conducted to address the first and second objectives. This study involved active data collection from a group of children with arterial ischemic stroke and healthy demographically equivalent control children. The third objective was addressed in Study 2, where a large and varied retrospective sample of children with arterial ischemic stroke enabled an examination of the effects of age at stroke, time since stroke, and lesion location.

## **STUDY 1: ACTIVE DATA COLLECTION**

### **The Present Study: Objectives and General Hypotheses**

The purpose of the current project was, firstly, to examine multiple domains of executive functioning in children aged 6 to 14 with a history of arterial ischemic stroke. For this purpose, a standardized empirically derived parent-questionnaire was used (the BRIEF) for its ability to concisely measure EFs across eight domains as they manifest in daily behaviours and real-life functioning of the child. A working memory test battery consisting of a series of standardized laboratory tasks was also administered to children in order to comprehensively assess this important EF skill. Additionally, academic achievement and social-emotional competence were assessed due to their empirical and theoretical relation to executive functioning ability. These important outcome variables serve as indicators of quality of life and overall functioning in various life domains. For all measures, children with a history of stroke were compared to demographically equivalent healthy control children.

The following were the hypotheses for the current project:

**Prediction 1.** It was hypothesized that children with a history of stroke would perform poorly on neuropsychological tests of EF, academic achievement, and social/behavioural competence relative to age-matched controls. Poor performance in working memory and arithmetic were particularly expected.

**Prediction 2.** It was hypothesized that a relationship would exist between EF and the outcome variables, such that EF performance would predict academic achievement and social-emotional competence. It was thought that working memory and other metacognitive EFs would be most associated with academic achievement, while behavioural regulatory EF would be predictive of social-emotional competence.

**Prediction 3.** It was hypothesized that age at stroke would be related to performance in all domains, such that stroke incurred the perinatal period (before 1 month) or in late childhood (age 6-14) would have poorest outcomes. Thus, it was expected that the effect of age at stroke on EF, academics, and social-emotional functioning would be non-linear, and that data points would exhibit a curvilinear relationship.

## **Method**

### **Participants**

#### *Stroke participants.*

This study included 32 children aged 6 to 14 with a history of unilateral arterial ischemic stroke. At the time of participation, the pediatric stroke patients were enrolled in the Children's Stroke Outcome Study at The Hospital for Sick Children in Toronto. Caregivers were contacted by phone to inform them of the current study and determine interest in participation. The following were the criteria for stroke group inclusion: (1) a single arterial ischemic infarction documented on magnetic resonance imaging (MRI) or computed tomography (CT); (2) arterial ischemic stroke before the age of 14 years; (3) the child was at least 6 months post-stroke; and (4) fluency in English. Exclusion criteria consisted of: (1) bilateral lesions; (2) multiple strokes; (3) preterm birth (less than 36 weeks gestation); (4) hypoxic-ischemic encephalopathy; (5) sickle cell disease; (6) psychosis; (7) moya moyo disease (a rare cerebrovascular disorder caused by blocked arteries at the base of the brain) ; (8) seizure disorders; and (9) any other neurological disorders (e.g. brain injury, malignancy, etc.). Children with Attention Deficit Hyperactivity Disorder (ADHD) were not excluded from study participation since the pediatric stroke literature has indicated that attention problems are quite common in this population (Max, Matthews, Lansing, Robertson, & Fox, 2002). In addition, children with learning disabilities were not

excluded since the investigation of academic achievement was a primary objective of the current study.

***Control participants.***

A sample of 32 age and sex matched healthy control children were recruited via local advertisement and from the siblings of patients with stroke. Children were excluded from the control group if they had experienced a head injury and/or if they had a condition that could impact neurodevelopment, such as premature birth (less than 36 weeks gestation), epilepsy, diabetes, or thyroid dysfunction.

**Procedure**

Informed consent was obtained from caregivers. The testing procedure and confidentiality were also explained to the youth participants and their assent was obtained prior to testing. Testing was conducted at The Hospital for Sick Children and at York University, depending upon the location preference of parents. All participants completed the Working Memory Test Battery for Children (WMTB-C; Pickering & Gathercole, 2001) and intelligence was assessed using the Wechsler Abbreviated Scale of Intelligence – Second Edition (WASI-II; Wechsler, 1999). Participants also completed the Calculation, Math Fluency, and Spelling subtests from the Woodcock-Johnson Tests of Achievement-Third Edition (WJ-III; Woodcock, McGrew, & Mather, 2001). Parents were asked to complete the Behavior Rating Inventory of Executive Function (BRIEF; Gioia et al., 2000a), the Behavior Assessment System for Children – Second Edition (BASC-2; Reynolds & Kamphaus, 2004) and a demographic questionnaire while their children engaged in testing. At the conclusion of testing, children and caregivers were provided with compensation, which consisted of a small prize for the child and transportation reimbursement. The results of testing and related feedback were compiled in a brief report that

was mailed to the caregivers.

## Measures

**Demographic questionnaire.** All caregivers were asked to complete a demographic questionnaire in order to collect information regarding participants' developmental, medical, and family histories. Maternal and paternal education was rated on an eight-point scale (1 = some elementary school; 2 = completed elementary school; 3 = some high school; 4 = completed high school; 5 = some college; 6 = completed college; 7 = university degree; 8 = postgraduate degree). Family income was rated on a six-point scale (1 = under \$20,000; 2 = \$20,001-\$30,000; 3 = \$30,001-\$40,000; 4 = \$40,001-\$50,000; 5 = \$50,001-\$80,000; 6 = over \$80,000).

**BRIEF (Gioia et al., 2000a).** Caregivers completed the BRIEF, which is an 86 item questionnaire designed to evaluate EFs of children and youth between the ages of 5 and 18 years. The BRIEF produces eight theoretically and empirically derived subscales, each representing a specific aspect of EF: Inhibit, Shift, Emotional Control, Initiate, Working Memory, Plan / Organize, Organization of Materials, and Monitor. Caregivers are required to rate the frequency of behaviours that represent overt manifestations of EFs in children using a 3 point scale of "never", "sometimes" or "often". The eight EF subscales produce two indices and one global EF composite: the Behavioral Regulation Index, Metacognition Index, and the Global Executive Composite. T-scores (M=50, SD=10) and percentiles can be derived for the subscales, indices and composite, and higher T-scores are indicative of greater executive dysfunction. T-scores that are equal to or greater than 65 are representative of clinical impairment.

The BRIEF contains a negativity scale and an inconsistency scale to assess the validity of responses given on the questionnaire. Internal consistency reliability is high, ranging from 0.80 to 0.98. Test-retest reliability on the BRIEF is also high and generally ranges from 0.76 to 0.85



for the various subscales and indices on the parent-rated normative sample (Gioia, Isquith, Guy, & Kenworthy, 2000b).

***BASC-2, parent version (Reynolds & Kamphaus, 2004).*** Caregivers also completed the BASC-2 as a standardized measure of youth's social-emotional functioning in everyday life. The BASC-2 is a parent questionnaire designed to measure behavioural problems in children between the ages of 2 to 5 (preschool form), 6 to 11 years (child form), and 12 to 21 years (adolescent form). Caregivers are required to rate the frequency of current behavioural problems on a 4-point scale of "not true", "sometimes", "often", or "almost always". The BASC-2 produces 14 primary scales (activities of daily living, adaptability, aggression, anxiety, attention problems, atypicality, conduct problems, depression, functional communication, hyperactivity, leadership, social skills, somatization, and withdrawal), 7 content scales (anger control, bullying, developmental social disorder, emotional self-control, executive functioning, negative emotionality, and resiliency), and 4 composite scales (adaptive skills, behavioral symptoms index, externalizing problems, and internalizing problems). The Behavioral Symptoms Index along with the Social Skills, Withdrawal, Atypicality, Aggression, and Conduct Problems primary scales were of interest in the present research study. These were the scales selectively analyzed.

On the BASC-2, T-scores ( $M=50$ ,  $SD=10$ ) and percentiles can be derived for each primary, content, and composite scale. For clinical scales, a T-score equal to or greater than 70 is representative of clinical impairment. For adaptive scales (e.g. Social Skills), a T-score equal to or less than 30 is representative of clinical impairment. The BASC-2 forms report good mean internal-consistencies (.80s to .90s for composites; .60s to .90s for individual scales) and test-retest reliability ranging from .70s to .90s. The manual and an independent review also report

good construct-validity, factor analyses, and concurrent-validity with other well-established behavioral scales (Community-University Partnership, 2011).

**WASI-II (Wechsler, 1999).** The WASI-II is an abbreviated, two or four subtest version of the Wechsler Intelligence Scales for Children - Fourth edition (WISC-IV; Wechsler, 2003) that is standardized for use among individuals aged 6 to 90 years. The WASI-II produces Verbal Comprehension, Perceptual Reasoning, and Full-Scale IQ scores. In the current study, each participant's intellectual functioning was measured using the Matrix Reasoning and Vocabulary subtests of the WASI-II (two-subtest version). This allowed for a quick and accurate estimate of Full Scale IQ that was not strongly biased by motor control abilities. Internal consistency reliability coefficients of the WASI-II range from 0.88 to 0.96 for Matrix Reasoning and 0.90 to 0.98 for Vocabulary. Stability coefficients for test-retest reliability have been found to range from 0.87 to 0.92. A correlational study found a strong relationship between WASI-II full scale IQ scores and the full scale IQ scores of the WAIS-III, thereby demonstrating concurrent validity; the correlation coefficients were 0.87 and 0.92 for the two and four subtest versions of the WASI, respectively (Garland, 2005).

**WMTB-C (Pickering & Gathercole, 2001).** The WMTB-C is a 10 subtest standardized measure of working memory that is designed for youth ranging from 5 to 15 years of age. Four subtests from this test battery were used to assess the central executive, phonological loop, and visuospatial sketchpad components of working memory. The administered subtests were: Word List Recall, Block Recall, Counting Recall, and Backwards Digit Recall. Standard scores ( $M = 100$ ,  $SD = 15$ ) are calculated for each subtest. The mean test-retest reliability of these subtests are .72, .53, .61, and .62, respectively (Gathercole, Pickering, Ambridge, & Wearing, 2004). The validity of the WMTB-C is also satisfactory, as internal factor analyses confirm the three factor

model of working memory. The measure also possesses adequate levels of internal validity, where significant correlations have been found between the phonological loop ( $r$  range = 0.54-0.72), visuospatial sketchpad ( $r$  range = 0.30-0.68), and central executive ( $r$  range = 0.27-0.63) measures. The following four subtests from the WMTB-C were administered:

1. Word List Recall – This subtest was used to measure the phonological loop component of working memory. Participants were asked to recall words in the order that they were presented. The first level begins with one word and the number increases until the child is unable to recall 4 trials of words within a level. The number of words the child is able to recall in their last successful span is used to indicate their phonological loop capacity.
2. Block Recall – This subtest measures the visuospatial sketchpad component of working memory. The examiner taps a set of blocks, and the child is asked to tap the blocks in the same sequence. The initial level begins with one block to recall and the number increases until the child is unsuccessful at four trials within a level. The number of blocks the child is able to recall in their last successful span is used to indicate their visuospatial sketchpad functioning.
3. Counting Recall – This subtest is a non-verbal measure of the central executive. Participants were presented with a booklet displaying one to six dots in an array and were asked to count the number of dots. They were then shown additional arrays and, again, asked to count the number of dots. Finally, children were asked to recall the number of dots presented in each array previously displayed. Initial trials begin with one dot array and each level increases by one dot array. Testing is discontinued once the child is unsuccessful at four trials within a level.
4. Backward Digit Recall – This subtest is a verbal measure of the central executive

component of working memory. Participants were required to recall the sequence of digits spoken aloud by the examiner in reverse order. Initial trials begin with two digits and each level increases by one digit. Testing is discontinued once the child is unable to recall four trials at a level.

**WJ-III (Woodcock et al., 2001).** Children's academic abilities were assessed using the Calculation, Math Fluency, and Spelling subtests of the WJ-III test battery of achievement. Thus, select academic abilities were measured, with a particular focus on arithmetic. The Calculation subtest is a paper and pencil test of math achievement which measures the participant's ability to perform mathematical computations, such as addition, subtraction, multiplication, and division. The test also includes some geometric, trigonometric, logarithmic, and calculus operations. Questions are arranged in order of difficulty, and the test taker's starting point is based on an estimate of their grade-based computational skill. The Spelling subtest is a measure of the ability to write orally presented words, which become increasingly difficult to spell. The test taker's starting point is based on an estimate of their grade-based spelling skill. The Calculation and Spelling tests are discontinued when the examinee obtains six consecutive scores of zero due to incorrect or incomplete responses. Math Fluency is a timed test of addition and subtraction. Children complete as many questions as possible within a 3 minute time limit. The total score for each subtest reflects the number of correct responses. Standard scores ( $M=100$ ,  $SD=15$ ) and percentile ranks are computed as an indication of the child's performance relative to peers.

Internal consistency reliability is high for individual tests (ranging from .80s to .90s) as well as for subject clusters (.90s). Test-retest reliability studies spanning 1 year intervals produced high median reliabilities (.80s to .90s). The achievement tests also have acceptable predictive validity, ranging within the .70s. In addition, the total achievement score correlates

well with other achievement tests, thereby demonstrating convergent validity (Schrack, McGrew, & Woodcock).

### **Statistical Analyses**

Firstly, data was analyzed to ensure that it met all assumptions of parametric tests. Homogeneity of variance across groups was assessed using Levene's Test. Normality was determined through the Shapiro-Wilk test, skewness values (values over  $\pm 2$  are indicative of non-normality), and by analyzing graphical representations of data distributions separated by group. An alpha significance level of .05 was adopted, and Holm's sequential Bonferroni procedure (Holm, 1979) was used to adjust for multiple comparisons by controlling the family-wise error rate. This approach controls for type I error inflation due to multiplicity, while maximizing power. Partial eta-squared values were computed as measures of effect size, where 0.01 = small, 0.06 = medium, 0.13 = large (Cohen, 1988). A one-tailed  $p$ -value was used for a statistical test result when the hypothesis was directional, and a two-tailed  $p$ -value was used for a statistical test result when the hypothesis was non-directional.

Chi-Square tests were conducted to compare groups on categorical demographic variables. A Welch t-test was used to examine potential differences in intelligence amongst the control and stroke groups. Potential differences between the stroke and control groups on each of the scales (WMTB-C, BRIEF, BASC-2, WJ-III) was tested using separate Analysis of Variance (ANOVAs) for each subscale comparison. Welch's  $F$  statistic was used to adjust for the effects of variance heterogeneity. Predicted variable relationships were investigated via correlation matrices. In addition, hierarchical linear regression analyses were carried out to examine whether scores on the BRIEF were significant predictors of scores on the 1) WJ-III and 2) BASC-2. Full Scale IQ was entered in the first step of hierarchical linear regression analyses in order to

account for the effects of intelligence. Scatter plots were constructed to visually examine the relationship between age at stroke and cognitive/behavioural outcomes, and determine eligibility for linear or non-linear regression.

## Results

### Demographic and Clinical Characteristics

Demographic and clinical characteristics of participants were determined from the demographic questionnaire completed by parents. In addition, a review of health records provided information on the neurological characteristics of stroke participants. Group comparisons of categorical demographic variables were made through Chi-Square tests. Groups did not differ in respect to sex [ $\chi^2(1) = 1.60, p = .311$ ], maternal education, [ $\chi^2(5) = 10.03, p = .074$ ], paternal education, [ $\chi^2(6) = 8.47, p = .206$ ], family income, [ $\chi^2(4) = 2.61, p = .626$ ], ethnicity, [ $\chi^2(5) = 6.28, p = .280$ ], or parental marital status [ $\chi^2(2) = 1.01, p = .601$ ]. A Welch t-test revealed that the stroke and control groups were also comparable with respect to age at assessment [ $t(59) = 1.23, p = .225$ ]. In stroke participants, the average age of stroke was 1.37 years, with a mean of 8.20 years since stroke. The majority of patients incurred stroke during the perinatal period. In regards to lesion location, 53% of stroke participants had cortical stroke, whereas 19% presented with subcortical stroke, and 28% had combined stroke to both cortical and subcortical regions. A summary of the demographic and neurological characteristics of stroke and control participants is presented in Table 1.

**Table 1.** Demographic characteristics of stroke and control participants and clinical characteristics of stroke participants

	<b>Stroke</b>	<b>Control</b>
Number of participants	32	32
Males, no. (%)	21 (65.6)	16 (50)
Age at assessment, mean (SD)	9.51y (2.72)	8.75y (2.16)
Maternal education <sup>1</sup> , mean (SD)	6.00 (1.44)	6.84 (1.08)
Paternal education <sup>1</sup> , mean (SD)	5.89 (1.64)	6.81 (1.17)
Family Income <sup>2</sup> , mean (SD)	5.26 (1.57)	5.47 (1.08)
Ethnicity		
African origin	3	2
Asian Am./Asian Pacific Islander	3	6
Latino-a/Hispanic	0	3
European origin/White	19	12
Bi-racial/Multi-racial	4	4
Other	3	5
Age at stroke, mean (SD)	1.37y (2.51)	
Age at stroke, no. of participants		
Perinatal	22	
1 month-5 years	7	
6-14 years	3	
Time since stroke, years, mean (SD)	8.20 (3.91)	
Lesion location		
Cortical	17	
Subcortical	6	
Combined	9	

1. Education is rated on an eight-point scale (see methods section for details)

2. Family income is rated on a six-point scale (see methods section for details)

Prior to analysis, intelligence variables were examined for parametric assumption agreement. Levene's test indicated that the assumption of homogeneity of variances was met for between group comparisons of each intellectual index. Graphical checks demonstrated that the IQ distributions for the stroke group were slightly negatively skewed, while the IQ distributions for the control group were slightly positively skewed. Shapiro-Wilk normality tests and skewness values all indicated that the distributions were not significantly skewed and were within the range of acceptability. One-factor, between subjects ANOVAs were conducted to

compare intellectual outcomes on the WASI-II. The stroke group was found to have significantly lower mean scores in Full Scale IQ, Vocabulary, and Matrix Reasoning. Despite this difference, both groups possessed mean scores that were within the average range of functioning. Partial eta-squared effect sizes were strong for Full Scale IQ and Vocabulary and of medium strength for Matrix Reasoning. A summary of the descriptive and inferential statistics regarding intellectual outcomes is presented in Table 2.

**Table 2.** Intelligence (WASI-II) scores and between subjects ANOVA results for stroke and control participants

<b>Intellectual Index<sup>1</sup></b>	<b>Stroke mean (SD)</b>	<b>Control mean (SD)</b>	<b>F-value</b>	<b>df</b>	<b>p-value<sup>2</sup></b>	<b>Partial Eta-Squared</b>
Full Scale IQ, Standard score	92.55 (17.60)	108.72 (17.37)	13.47	1, 61	<.001*	.18
Vocabulary, T-score	46.81 (11.92)	56.56 (11.00)	11.40	1, 61	<.001*	.16
Matrix Reasoning, T-score	47.74 (12.15)	53.25 (10.96)	3.57	1, 61	.032*	.06

1. Intelligence subtests are in standard scores

2. One-tailed *p*-values (directional hypotheses)

\*significant after application of the sequential Holm-Bonferroni procedure

### Working Memory Outcomes

Prior to analysis, working memory variables were examined for parametric assumption agreement. Levene's test indicated that the assumption of homogeneity of variances was met for between group comparisons of each working memory subtest. Normality was also satisfactory. Graphical checks, Shapiro-Wilk tests, and skewness values all indicated that the distributions for each working memory subtest did not significantly deviate from a normal distribution. This was true for both stroke and control groups. One-factor, between subjects ANOVAs were conducted to compare group performance on the Word List Recall, Block Recall, Counting Recall, and



Backward Digit Recall subtests of the WMTB-C. The stroke group was found to have significantly lower mean standard scores on all working memory subscales. Partial eta-squared effect sizes were strong for group differences on the Word List Recall and Block Recall subtests, while group differences on the Counting Recall and Backward Digit Recall subtests were of medium effect. With the exception of Backward Digit Recall, more variability was observed in the scores of stroke participants as evidenced by slightly larger standard deviations. A proportional analysis revealed that 31% of stroke participants attained Word List Recall standard scores of 85 or lower ( $\leq$  one standard deviation below the normative mean). This is in contrast to 0% of control participants. A summary of the descriptive and inferential statistics regarding working memory outcome is presented in Table 3.

**Table 3.** Working memory (WMTB-C) scores and between subjects ANOVA results for stroke and control participants

<b>Working Memory Subtest<sup>1</sup></b>	<b>Stroke mean (SD)</b>	<b>Control mean (SD)</b>	<b>F-value</b>	<b>df</b>	<b>p-value<sup>2</sup></b>	<b>Partial Eta-Squared</b>
Word List Recall	98.55 (19.18)	114.13 (16.17)	13.58	1, 62	<.001*	.18
Block Recall	96.66 (18.51)	107.91 (14.39)	10.69	1, 62	.001*	.15
Counting Recall	90.31 (19.09)	101.16 (17.09)	6.51	1, 61	.007*	.10
Backward Digit Recall	90.55 (14.97)	101.38 (19.06)	6.93	1, 60	.006*	.10

1. Working memory subtests are in standard scores

2. One-tailed *p*-values (directional hypotheses)

\*significant after application of the sequential Holm-Bonferroni procedure

### **Executive Functioning Outcomes**

Behavioural Executive Functioning data from the BRIEF was examined for parametric test assumption agreement. Graphical displays and skewness values revealed negatively skewed distributions for the stroke group and positively skewed distributions for the control group on the

majority of the BRIEF subscales. Skewness values were still within the range of acceptability, but Shapiro-Wilk tests indicated that the normality deviations were significant. Non-parametric tests were not appropriate as the stroke and control group distributions were skewed in opposite directions. Although data transformation carries several disadvantages (e.g. data is not in original units, thereby complicating interpretation), various transformations were applied in an attempt to normalize the data. Square, cube, square root, and natural log transformations failed to normalize the distributions. Since the sample distributions were not severely skewed (i.e. skewness values were within the  $\pm 2$  range) and ANOVA tends to be robust to non-normal distributions, the decision was made to use one-factor between subjects AVOVAs to make group comparisons on BRIEF data. However, the Welch's F was used to correct for heterogeneous variances among groups since Levene's test was significant for most BRIEF subscales.

With the exception of Organization of Materials, significant group differences were found on all BRIEF scales, indices, and composites. In each case the stroke group had the higher mean T-score. On the BRIEF, higher T-scores are representative of poorer functioning. Partial eta-squared effect sizes were strong for the Behavioral Regulation Index, Inhibit, Shift, Emotional Control, the Metacognition Index, Working Memory, Plan/Organize, and the Global Executive Composite. The effect for Working Memory was particularly strong, with a partial eta-squared value of 0.24. Of the remaining scales, group differences in Initiate and Monitor were of medium effect and Organization of Materials was a small effect. Across BRIEF scales, more variability in functioning was observed in stroke participants, as evidenced by larger standard deviations. A proportional analysis revealed that 40.0% of stroke participants possessed Global Executive Composite scores in the clinically significant range (T-scores of 65 or greater). This is in contrast to only 6.3% of control participants. A summary of the descriptive and

inferential statistics regarding working memory outcome is presented in Table 4.

**Table 4.** Executive Functioning (BRIEF) scores and between subjects ANOVA results for stroke and control participants

EF Scale <sup>1</sup>	Stroke mean (SD)	Control mean (SD)	Welch F-value	Welch df	p-value <sup>2</sup>	Partial Eta- Squared
<b>Behavioral Regulation Index</b>	57.93 (15.43)	45.78 (10.00)	13.35	1, 49.2	<.001*	.19
Inhibit	56.50 (15.90)	46.28 (7.98)	10.22	1, 42.2	.002*	.15
Shift	58.93 (16.40)	46.88 (11.15)	11.31	1, 50.7	<.001*	.16
Emotional Control	56.23 (12.39)	46.59 (10.19)	11.11	1, 56.3	.001*	.16
<b>Metacognition Index</b>	59.47 (13.99)	49.22 (10.75)	10.36	1, 54.4	.001*	.15
Initiate	58.90 (14.59)	50.34 (11.47)	6.53	1, 55.0	.007*	.10
Working Memory	61.60 (14.96)	48.16 (9.18)	17.90	1, 47.5	<.001*	.24
Plan/Organize	58.90 (12.25)	50.09 (11.01)	8.82	1, 58.3	.002*	.13
Organization of Materials	53.33 (9.85)	50.41 (8.71)	1.53	1, 58.0	.111	.03
Monitor	56.00 (13.14)	47.78 (11.86)	6.65	1, 58.4	.006*	.10
<b>Global Executive Composite</b>	59.33 (14.47)	47.94 (10.59)	12.39	1, 52.9	<.001*	.17

1. All BRIEF scales, indexes, and composites are in T-scores

2. One-tailed *p*-values (directional hypotheses)

\*significant after application of the sequential Holm-Bonferroni procedure

### Social-Emotional Behavioural Outcomes

The Social Skills, Withdrawal, Atypicality, Conduct Problems, and Aggression scales from the BASC-2 were selectively analyzed as behavioural social-emotional outcomes in stroke and control participants. Firstly the data was examined for parametric test assumption agreement. Shapiro-Wilk tests indicated significant normality deviations for the stroke group on the

Withdrawal and Atypicality subscales and significant normality deviations for the control group on the Atypicality subscale and the Behavioral Symptoms Index. However, all variable skewness values were within the  $\pm 2$  range of acceptability and graphical checks displayed distributions that were not severely skewed. An attempt at data transformation was made to see if a function could create distributions more normal in shape. Square, cube, square root, and natural log transformations were applied to the Withdrawal, Atypicality, and Behavioral Symptoms data, but these functions failed to further normalize the distributions. Checks on the assumption of homogeneity of variance indicated significant differences in group variances on the Behavioral Symptoms Index and the Withdrawal, Atypicality, and Aggression scales. The ANOVA test was selected for its robustness to reasonable deviations of normality and its ability to correct for variance heterogeneity by use of the Welch statistic. Welch statistics correct for the effects of unequal variances and can also be applied to data that does not violate the variance assumption since it does not lead to a loss of power.

One-factor between subjects Welch ANOVAs revealed significant group differences on the Atypicality, Aggression, and Conduct Problems scales and on the Behavioral Symptoms Index. The stroke group obtained higher mean T-scores on these scales, which represents a greater degree of behavioural and emotional problems. Partial eta-squared effect sizes were strong for the Behavioral Symptoms Index, Atypicality scale, and Aggression scale, and a medium effect was noted for the Conduct Problems scale. A small effect was noted for the Social Skills and Withdrawal scales; these were the scales in which significant group differences were not found. Across BASC-2 scales, more variability in functioning was observed in stroke participants, as evidenced by larger standard deviations. A proportional analysis revealed that 23.3% of stroke participants attained Behavioral Symptoms Index scores in the clinically

significant range (T-scores of 70 or greater). This is in contrast to only 6.3% of control participants. A summary of the descriptive and inferential statistics regarding social-emotional behavioural outcome is presented in Table 5.

**Table 5.** Social-emotional behavioural (BASC-2) scores and between subjects ANOVA results for stroke and control participants

<b>BASC-2 Scale<sup>1</sup></b>	<b>Stroke mean (SD)</b>	<b>Control mean (SD)</b>	<b>Welch F-value</b>	<b>Welch df</b>	<b><i>p</i>-value<sup>2</sup></b>	<b>Partial Eta- Squared</b>
Social Skills	46.74 (12.32)	49.06 (10.94)	0.63	1, 59.7	.217	.01
<b>Behavioral Symptoms Index<sup>3</sup></b>	57.17 (14.39)	46.88 (8.78)	11.38	1, 47.4	<.001*	.16
Withdrawal	58.60 (14.63)	52.31 (12.66)	3.26	1, 57.5	.038	.05
Atypicality	59.50 (17.22)	47.25 (8.03)	14.06	1, 42.3	<.001*	.19
Aggression	52.90 (10.70)	44.78 (5.67)	11.58	1, 44.6	<.001*	.16
Conduct Problems	51.03 (10.98)	46.06 (6.65)	6.26	1, 49.3	.008*	.09

1. All BASC-2 scales, indexes, and composites are in T-scores

2. One-tailed *p*-values (directional hypotheses)

3. Behavioral Symptoms Index also includes problems with hyperactivity, attention, and depression

\*significant after application of the sequential Holm-Bonferroni procedure

### Academic Achievement Outcomes

Academic achievement outcomes in math and spelling were examined through analysis of WJ-III subtest data. Firstly, data was analyzed for parametric assumption agreement. Levene's test indicated that the homogeneity of variances assumption was satisfied for Calculation, Math Fluency, and Spelling subtests. Normality checks via Shapiro-Wilk statistical tests, skewness values, and graphical checks indicated acceptable distributions, with the exception of the Calculation distribution for the stroke group which was significantly negatively skewed. Transformations were applied in an attempt to normalize the data. The square transformation

succeeded at normalizing the stroke Calculation distribution; however, it caused the Control Calculation distribution to become significantly positively skewed. A trimming option was not adopted due to the small number of data points. The ANOVA test was selected for its robustness to reasonable deviations of normality.

One-factor between subjects ANOVAs were conducted to examine group differences on academic achievement. Tests revealed significant group differences on Calculation, Math Fluency, and Spelling. Relative to controls, the stroke group attained lower mean standard scores on these subtests, which represents lower academic achievement in the subject areas of math (timed and untimed) and spelling. Partial eta-squared effect sizes were strong for the Math Fluency and Spelling subtests, and of medium strength for the Calculation subtest. Similar variability in academic scores was observed amongst stroke and control participants, as indicated by standard deviation values which were large for both groups.

Chi-square analyses were conducted to examine the proportion of stroke participants impaired in each academic area and to determine whether this value statistically differs from the control group. Impairment in academics is commonly defined as performance equal to or greater than one standard deviation below the normative mean (16<sup>th</sup> percentile or lower). This definition was adopted for the current study. In Calculation, 40.0% of the stroke group was impaired in comparison to 17.6% of the control group,  $\chi^2(1) = 2.20, p = .131$ . In Math Fluency, 47.1% of the stroke group was impaired in comparison to 11.8% of the control group,  $\chi^2(1) = 5.10, p = .029$ . In Spelling, 23.5% were impaired in comparison to 5.9% of controls,  $\chi^2(1) = 2.11, p = .168$ . Thus, although there were a substantial portion of stroke participants impaired in each subject area, groups only differed on Math Fluency in respect to impairment. A summary of the descriptive and inferential statistics regarding academic achievement outcome is presented in Table 6.

**Table 6.** Academic achievement (WJ-III) scores and between subjects ANOVA results for stroke and control participants

<b>WJ-III Subtest<sup>1</sup></b>	<b>Stroke mean (SD)</b>	<b>Control mean (SD)</b>	<b>F-value</b>	<b>df</b>	<b><i>p</i>-value<sup>2</sup></b>	<b>Partial Eta- Squared</b>
Calculation	86.53 (21.55)	104.41 (26.55)	4.95	1, 35	.017*	.12
Math Fluency	85.00 (14.60)	98.76 (14.14)	6.19	1, 32	.009*	.16
Spelling	96.07 (15.30)	113.59 (18.44)	10.62	1, 32	.002*	.25

1. Academic subtests are in standard scores

2. One-tailed *p*-values (directional hypotheses)

\*significant after application of the sequential Holm-Bonferroni procedure

### **Relationship between EFs and Academic Achievement**

The relationship between EFs and academic achievement was investigated via correlational analysis, hierarchical linear regression, and graphical displays. Firstly, data were assessed for assumption agreement. The assumptions of linearity, independent errors, and homoscedasticity were met for all Pearson's correlations and linear regressions. In addition, collinearity diagnostics revealed acceptable tolerance and variance inflation (VIF) values for all hierarchical linear regressions. Outliers can have a substantial and adverse impact on correlation and regression results; accordingly, data were examined for notable outliers with influence. A single outlier was detected in the Calculation correlation and regression statistics in the stroke group (case 14). This case was far from the regression line, as the stroke participant attained a Calculation score that was more than five standard deviations below the normative mean. Leverage values and Cook's distance indicated that this value had a substantial influence on statistics, and thus was a significant outlier. This Calculation score value was removed from the correlation and regression statistics of the stroke group.

Pearson's correlations between EF scales and academic scores were conducted for the

stroke group. Correlations between the main indices and composites of the BRIEF (T-scores) and academic outcomes (standard scores) revealed several significant values. Metacognition and the Global Executive Composite yielded the strongest correlations with the academic outcomes, particularly in Calculation and Spelling. Only one significant correlation was found for the working memory subtests from the WMTB-C (standard scores). This correlation was between Word List Recall and Spelling and was of medium strength. A summary of EF-academic correlation outcomes for the stroke group is presented in Table 7.

**Table 7.** Stroke group Pearson's correlations between executive function scales (the main executive function indices of the BRIEF and the subtests of the WMTB-C) and academic achievement results of the WJ-III in math and spelling

EF Scale	Calculation	Math Fluency	Spelling
Metacognition Index	<b>-.68**</b>	<b>-.42*</b>	<b>-.76***</b>
Behavioral Regulation Index	-.37	-.15	<b>-.68**</b>
Global Executive Composite	<b>-.56**</b>	-.29	<b>-.76***</b>
Word List Recall	-.17	.15	<b>.43*</b>
Block Recall	.05	.09	.24
Counting Recall	.20	.07	.13
Backward Digit Recall	-.002	.12	.41

Note: Metacognition, Behavioral Regulation, and the Global Executive are indices/composites of the BRIEF. Remaining EF subscales are from the WMTB-C.

\*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

Pearson's correlations between EF scales and academic scores were also conducted for the control group. Correlations between BRIEF scales (T-scores) and academic outcomes (standard scores) revealed weak correlation coefficients that were non-significant. Some working memory subtests from the WMTB-C (standard scores) significantly correlated with academic



tests. Correlations were .50 or greater and large in effect. Notably, Spelling significantly correlated with three of four subtests (Word List Recall, Block Recall, and Backward Digit Recall). Calculation and Math Fluency significantly correlated with Backward Digit Recall. A summary of EF-academic correlation outcomes for the control group is presented in Table 8.

**Table 8.** Control group Pearson's correlations between executive function scales (the main executive function indices of the BRIEF and the subtests of the WMTB-C) and academic achievement results of the WJ-III in math and spelling

<b>EF Scale</b>	<b>Calculation</b>	<b>Math Fluency</b>	<b>Spelling</b>
Metacognition Index	-.24	-.26	-.13
Behavioral Regulation Index	-.10	-.24	.01
Global Executive Composite	-.19	-.27	-.07
Word List Recall	.41	.22	<b>.50*</b>
Block Recall	.40	.35	<b>.50*</b>
Counting Recall	.18	.01	.31
Backward Digit Recall	<b>.65**</b>	<b>.52*</b>	<b>.58**</b>

Note: Metacognition, Behavioral Regulation, and the Global Executive are indices/composites of the BRIEF. Remaining EF subscales are from the WMTB-C.

\*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

A hierarchical regression model was conducted to examine if Metacognition is a significant predictor of Calculation score in the stroke group, and whether this applies beyond the effects of intelligence (after accounting for Full Scale IQ score). In step one, Full Scale IQ was entered into the regression model and intelligence only accounted for 1% ( $R^2 = .01$ ) of the variation in Calculation outcome [ $F(1,16) = 0.09$ ,  $p = .767$ ], and was not a significant predictor. In step two, Metacognition was also added into the model. Together, Full Scale IQ and Metacognition score accounted for 50% ( $R^2 = .50$ ) of the variation in Calculation outcome in the

stroke group [ $F(2,15) = 7.38, p = .006$ ], and Metacognition score accounted for almost all of this variability ( $\Delta R^2 = .49$ ). Metacognition was a significant predictor of Calculation score in the stroke group and it made a statistically significant contribution to the regression model.

As a means of comparison, hierarchical regression analysis for Calculation outcome was also conducted in the control group. Step one [ $F(1,15) = 4.93, p = .042$ ] and step two [ $F(2,14) = 2.71, p = .101$ ] were non-significant, which indicated that intelligence and Metacognition did not make a significant contribution to the control group model. Table 9 presents a summary of hierarchical regression results for Calculation outcome in the stroke and control groups. In addition, Figure 1 displays a scatter plot of Calculation score (y-axis) graphed with Metacognition score (x-axis) for both groups.

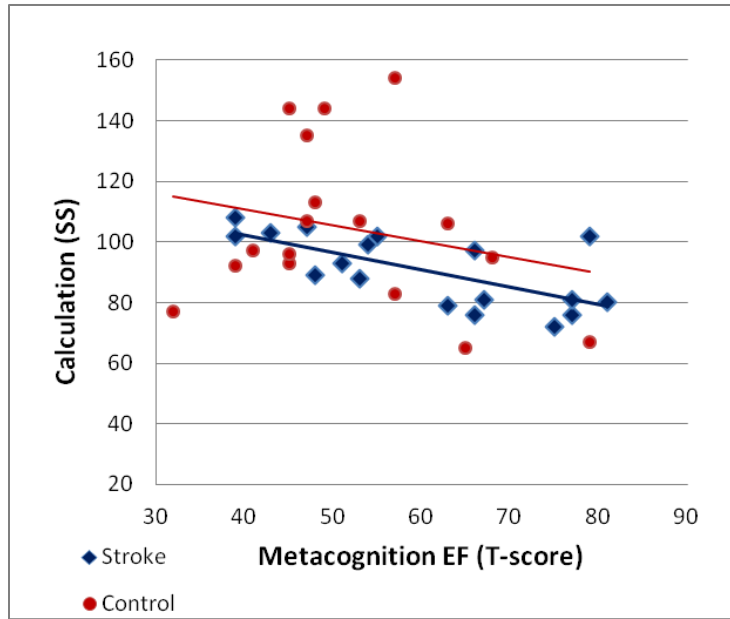
**Table 9.** Hierarchical linear regression model with Calculation score as the outcome variable for stroke and control groups

Group	Step	Predictor	B	$\beta$	$R^2$	$t$	$p$ -value
Stroke	1	FSIQ	.05	.08	.01	.30	.767
	2	FSIQ	-.14	-.19		-.98	.345
		Metacognition <sup>1</sup>	-.63	-.75	.50	-3.82	.002*
Control	1	FSIQ	.81	.50	.25	.45	.042
	2	FSIQ	.77	.48		2.09	.056
		Metacognition <sup>2</sup>	-.41	-.18	.28	-.79	.443

1. Note:  $\Delta R^2 = .49$

2. Note:  $\Delta R^2 = .03$

\* significant after application of the sequential Holm-Bonferroni procedure



**Figure 1.** Scatter plot depicting the relationship between Metacognition EF score (BRIEF) and Calculation subtest performance (WJ-III) in stroke and control groups

Another hierarchical regression model was conducted to examine if Metacognition is a significant predictor of Spelling score in the stroke group, and whether this applies beyond the effects of intelligence (after accounting for Full Scale IQ score). In step one, Full Scale IQ was entered into the regression model, and intelligence accounted for 24% ( $R^2 = .24$ ) of the variation in Spelling outcome, but was not a significant predictor [ $F(1,15) = 4.64, p = .048$ ]. In step two, Metacognition was also added into the model. Together, Full Scale IQ and Metacognition score accounted for 59% ( $R^2 = .59$ ) of the variation in Spelling outcome in the stroke group [ $F(2,14) = 9.99, p = .002$ ], and Metacognition score accounted for a large portion of this variability ( $\Delta R^2 = .35$ ). Metacognition was a significant predictor of Spelling score in the stroke group and it made a statistically significant contribution to the regression model.

As a means of comparison, hierarchical regression analysis for Spelling outcome was also conducted in the control group. Step one [ $F(1,15) = 5.43, p = .034$ ] and step two [ $F(2,14) = 2.59, p = .110$ ] were non-significant, which indicated that intelligence and Metacognition did not

make a significant contribution to the control group model. Table 10 presents a summary of hierarchical regression results for Spelling outcome in the stroke and control groups. In addition, Figure 2 displays a scatter plot of Spelling score (y-axis) graphed with Metacognition score (x-axis) for both groups.

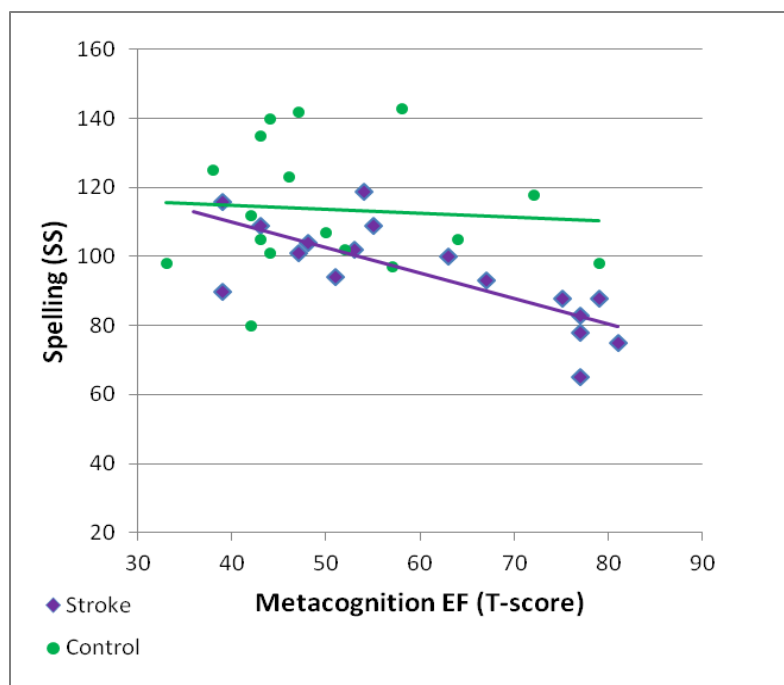
**Table 10.** Hierarchical linear regression model for stroke and control participants with Spelling score as the outcome variable

Group	Step	Predictor	B	$\beta$	$R^2$	$t$	$p$ -value
Stroke	1	FSIQ	.51	.49	.24	2.15	.048
	2	FSIQ	.16	.15		0.79	.445
		Metacognition <sup>1</sup>	-.66	-.68	.59	-3.46	.004*
Control	1	FSIQ	.58	.52	.27	2.33	.034
	2	FSIQ	.58	.51		2.21	.044
		Metacognition <sup>2</sup>	-.10	-.07	.27	-0.29	.775

1. Note:  $\Delta R^2 = .35$

2. Note:  $\Delta R^2 = .00$

\* significant after application of the sequential Holm-Bonferroni procedure



**Figure 2.** Scatter plot depicting the relationship between Metacognition EF score (BRIEF) and Spelling subtest performance (WJ-III) in stroke and control groups

### Relationship between EFs and Social-Emotional Functioning

The relationship between EFs and social-emotional functioning was investigated via correlational analysis, hierarchical linear regression, and graphical displays. Firstly, data was assessed for assumption agreement. The assumptions of linearity, independent errors, and homoscedasticity were met for all Pearson's correlations and linear regressions. In addition, collinearity diagnostics revealed acceptable tolerance and variance inflation (VIF) values for all hierarchical linear regressions. Outliers can have a substantial and adverse impact on correlation and regression results; accordingly, data was examined for notable outliers with influence. No outliers with substantial influence were noted.

Pearson's correlations between EF scales and social-emotional scales were conducted for the stroke group. The BASC-2 scales that had shown significant group differences and large effect sizes in prior analyses were included in the correlation matrix. All correlations between

BASC-2 scales (T-scores) and the main indices and composites of the BRIEF (T-scores) revealed significant coefficients that were strong in effect, with the exception of the Aggression and Metacognition correlation, which was Medium in strength. The Behavioral Regulation Index and the Global Executive Composite yielded the strongest correlations with the BASC-2 scales. Correlations were also conducted between the working memory WMTB-C subtests (standard scores) and BASC-2 scales. Results revealed five significant correlations of medium strength. A summary of EF and social-emotional correlation outcomes for the stroke group is presented in Table 11

**Table 11.** Stroke group Pearson's correlations between executive function scales (the main executive function indices of the BRIEF and the subtests of the WMTB-C) and select social-emotional scales of the BASC-2

EF Scale	BSI	Atypicality	Aggression	Conduct Problems
Metacognition Index	<b>.81***</b>	<b>.72***</b>	<b>.41*</b>	<b>.55**</b>
Behavioral Regulation Index	<b>.91***</b>	<b>.75***</b>	<b>.76***</b>	<b>.68***</b>
Global Executive Composite	<b>.89***</b>	<b>.78***</b>	<b>.58***</b>	<b>.67***</b>
Word List Recall	-.09	-.03	-.14	<b>-.31*</b>
Block Recall	-.15	-.15	-.17	-.12
Counting Recall	<b>-.46**</b>	<b>-.48**</b>	<b>-.33*</b>	-.13
Backward Digit Recall	-.29	<b>-.36*</b>	-.26	-.24

Note: Metacognition, Behavioral Regulation, and the Global Executive are indices/composites of the BRIEF. Remaining EF subscales are from the WMTB-C.

BSI = Behavioral Symptoms Index

\*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

Pearson's correlations between EF scales and social-emotional scores were also conducted for the control group. Correlations between BRIEF scales (T-scores) and BASC-2

scales (standard scores) revealed medium to strong correlation coefficients that were significant. However, the BASC-2 Conduct Problems scale did not have any significant correlations with EF scales. One working memory subtest from the WMTB-C (standard scores) significantly correlated with a social-emotional subscale. This correlation was between Backward Digit Recall and Atypicality, and this coefficient was medium in strength. A summary of EF and social-emotional correlation outcomes for the control group is presented in Table 12.

**Table 12.** Control group Pearson's correlations between executive function scales (the main executive function indices of the BRIEF and the subtests of the WMTB-C) and select social-emotional scales of the BASC-2

EF Scale	BSI	Atypicality	Aggression	Conduct Problems
Metacognition Index	.76***	.69***	.35*	.28
Behavioral Regulation Index	.82***	.65***	.54**	.27
Global Executive Composite	.82***	.72***	.45**	.29
Word List Recall	.01	-.22	.15	-.27
Block Recall	.00	-.05	-.08	.13
Counting Recall	.26	.05	.27	.13
Backward Digit Recall	-.28	-.36*	-.26	-.15

Note: Metacognition, Behavioral Regulation, and the Global Executive are indices/composites of the BRIEF. Remaining EF subscales are from the WMTB-C.

BSI = Behavioral Symptoms Index

\*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

A hierarchical regression model was conducted with stroke group data to examine if behavioral regulation EF ability is a significant predictor of behavioral symptoms (social-emotional issues), as measured by the Behavioral Symptoms Index of the BASC-2. Analyses also investigated whether this relationship would apply beyond the effects of intelligence (after

accounting for Full Scale IQ score). In step one, Full Scale IQ was entered into the regression model and intelligence accounted for 16% ( $R^2 = .16$ ) of the variation in Behavioral Symptoms [ $F(1,27) = 5.11, p = .032$ ], and was not a significant predictor after the application of the sequential Holm-Bonferroni procedure. In step two, the Behavioral Regulation Index of the BRIEF was also added into the model. Together, Full Scale IQ and the Behavioral Regulation Index score accounted for 83% ( $R^2 = .83$ ) of the variation in Behavioral Symptom outcome in the stroke group [ $F(2, 26) = 61.08, p < .001$ ], and Behavioral Regulation score accounted for a large portion of this variability ( $\Delta R^2 = .67$ ). Behavioral Regulation was a significant predictor of Behavioral Symptoms score in the stroke group and it made a statistically significant contribution to the regression model.

As a means of comparison, hierarchical regression analysis for Behavioral Symptoms outcome was also conducted in the control group. Step one was not significant [ $F(1,30) = 0.12, p = .727$ ], which indicated that Full Scale IQ alone did not successfully predict Behavioral Symptoms. In addition, intelligence did not account for any of the variability in Behavioral Symptoms outcome (0.0%;  $R^2 = .00$ ). In step two, Behavioral Regulation was added to the model. Step two was significant [ $F(2, 29) = 29.43, p < .001$ ] and accounted for a large portion of the variability in Behavioral Symptoms outcome (67%;  $R^2 = .67$ ). Behavioral Regulation accounted for all of this variability ( $\Delta R^2 = .67$ ). Thus, Behavioral Regulation was a significant predictor of Behavioral Symptoms score in the control group and it also made a statistically significant contribution to the regression model. Table 13 presents a summary of hierarchical regression results for Behavioral Symptoms outcome in the stroke and control groups and Figure 3 displays a scatter plot of Behavioral Symptoms score (y-axis) graphed with Behavioral Regulation score (x-axis) for both groups.



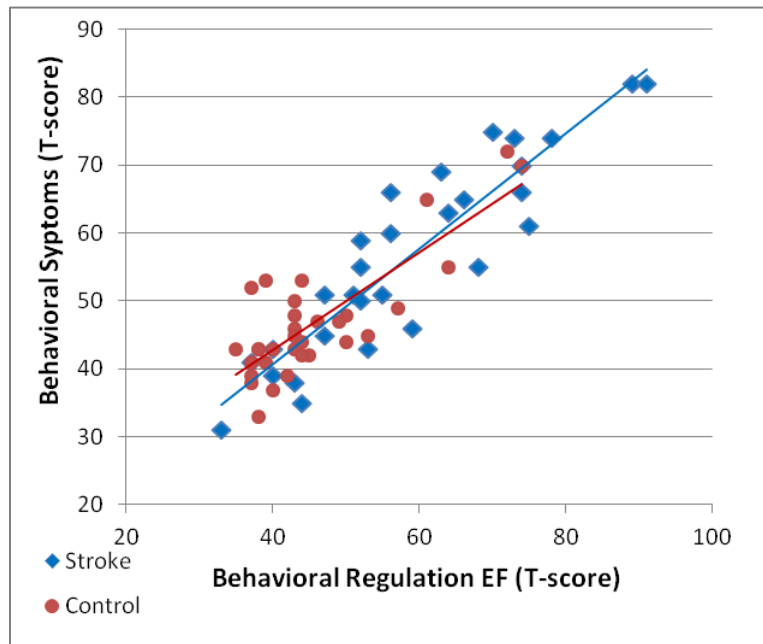
**Table 13.** Hierarchical linear regression model for stroke and control participants with Behavioral Symptoms Index score (BASC-2) as the outcome variable

Group	Step	Predictor	B	$\beta$	$R^2$	$t$	$p$ -value
Stroke	1	FSIQ	-.32	-.40	.16	-2.26	.032
	2	FSIQ	.04	.04		.47	.640
		Behavioral Regulation <sup>1</sup>	.87	.93	.83	9.93	<.001*
Control	1	FSIQ	.03	.06	.00	0.35	.727
	2	FSIQ	.02	.05		0.43	.672
		Behavioral Regulation <sup>2</sup>	.72	.82	.67	7.65	<.001*

1. Note:  $\Delta R^2 = .67$

2. Note:  $\Delta R^2 = .67$

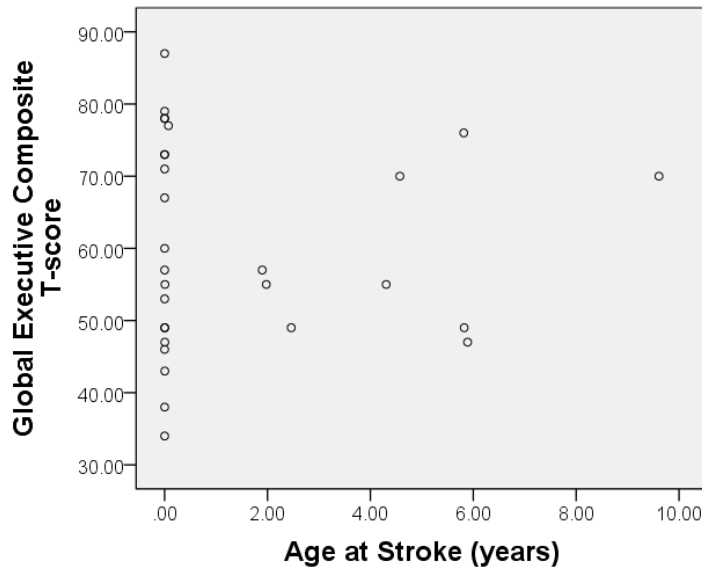
\* significant after application of the sequential Holm-Bonferroni procedure



**Figure 3.** Scatter plot depicting the relationship between Behavioral Regulation EF score (BRIEF) and Behavioral Symptoms score (BASC-2) in stroke and control groups

### **Age at Stroke Analysis**

Scatter plots were produced to visually examine a potential relationship between age at stroke (years) and outcomes in EF, academics, and social-emotional functioning. Six graphs were created, each with age at stroke on the x-axis. Word List Recall, Metacognition, Global Executive, Calculation, Spelling, and Behavioral Symptoms were placed on the y-axis. For all graphs, data points clustered toward the very beginning of the x-axis, as many stroke participants experienced stroke early in development around the perinatal period. The lack of data points for stroke during early and late childhood made it difficult to discern relationships. The data points appeared dispersed on the y-axis, and no evidence of a linear or curvilinear relationship was present. An example of such a graph is shown below; Figure 4 depicts the relationship between age at stroke in years and T-score for the Global Executive Composite of the BRIEF. Linear and curvilinear  $R^2$  coefficients were calculated for each graph. All were very low, and ranged from 0.00 to 0.03. This indicated that for the collected data, age at stroke did not account for variation in EF, academic, and social-emotional outcomes in children with stroke. Due to the lack of a linear or curvilinear relationship, the data were not analyzed using regression.



**Figure 4.** Scatter plot depicting the relationship between age at stroke and Global Executive Composite T-score (BRIEF) in stroke participants

## Discussion

The aim of this study was to examine executive functioning, academic achievement, and social-emotional outcomes in children with a history of arterial ischemic stroke. It was believed that these abilities would be lower in children with stroke relative to typically developing children; in particular it was predicted that children with stroke would have reduced working memory capacity and impairment in the ability to perform arithmetic. Poor social functioning was also expected. Moreover, the current study investigated the relationships between executive functions and the other outcome variables, as it was believed that executive functioning would directly predict academic ability and social-emotional competency in the stroke group. This is due to the supervisory role that EFs play in human cognition (Shallice, 2004). Results generally supported the aforementioned hypotheses. In particular, specific difficulty in arithmetic ability and parent reported working memory was noted. Relative to controls, an elevation in behavioural symptoms was also observed. Moreover, predicted variable relationships were confirmed,

suggesting that EFs have a strong contributory role in important areas of cognition and behaviour. Overall, scores were within the average to below average range in children with stroke and indicated the presence of subtle deficits.

### **Working Memory Outcomes**

As hypothesized, youth with a history of stroke performed significantly worse than controls on all four subtests of the WMTB-C. This finding was supported by the Working Memory subscale of the BRIEF, where parent report indicated significantly more working memory dysfunction in the stroke group compared to controls. Group differences on the WMTB-C revealed strong effects for Word List Recall and Counting Recall and medium effects for Counting recall and Backward Digit Recall. Very strong effects were found for group differences on the Working Memory scale of the BRIEF, with group differences accounting for 24% of variability in working memory ability.

Although statistically significant group differences in working memory were found, the mean scores on WMTB-C subtests for children with stroke fell within the average range (mean standard scores ranged from 90.3 to 98.5 for stroke participants). Likewise, the mean Working Memory T-score on the BRIEF approached clinical significance, but did not meet the T-score cutoff of 65 or greater ( $M = 61.60$ ). Results suggest subtle working memory difficulties in children with stroke and converge with working memory findings in existing pediatric stroke literature. Prior studies documented subtle deficits to the verbal central executive and phonological loop components of working memory in pediatric stroke (Lansing et al., 2004; Westmacott et al., 2009, 2010; White et al., 2000). The current study supplements the extant literature by confirming subtle working memory challenges in the verbal central executive (as shown by the Backward Digit Recall task), phonological loop (Word List Recall), visuospatial

sketchpad (Block Recall), and visual central executive (Counting Recall).

### **Executive Functioning Outcomes**

Parental ratings on the BRIEF indicated that relative to controls, youth with stroke had significantly higher scores on all behavioural EF scales and indices, with the exception of the Organization of Materials scale. Higher scores on the BRIEF are indicative of poorer behavioural executive functioning. Results suggest that youth with a history of stroke have increased difficulty with both the “hot” emotional aspects of EF and the “cool” problem solving oriented components. This was reflected by significantly poorer scores in both the Behavioral Regulation Index and the Metacognition Index (and the subscales subsumed within these indices). Behavioral regulatory EFs encompass the ability to inhibit an inappropriate response, make transitions, and modulate emotional responses. Metacognitive EFs encompass the ability to cognitively self-manage tasks (e.g. initiating, planning, and organizing) and monitor performance. The Organization of Materials scale was the single EF scale that did not display significant group differences. Thus, parent ratings suggest that children with a history of stroke do not experience trouble with aspects of organization that involve orderliness of work, play, and storage areas. Effect sizes supported the statistical results, with large effect sizes present for group differences in Metacognitive EFs and Behavioral Regulatory EFs, and a small effect was noted for Organization of Materials.

It is important to note that although BRIEF scores in the stroke group were significantly different from controls, none of the mean T-scores were within the range of clinical significance (all T-scores were <65). This indicates that, on average, stroke participants are displaying poor EF ability relative to controls, but abilities are not as severe as to be termed “impaired” or “dysfunctional.” Interestingly, when impairment rates were examined, it was found that 40% of

stroke participants possessed Global Executive Composite scores in the clinically significant range. This was in contrast to only 6.3% of control participants. This indicates variability in functioning among stroke participants, as this degree of dysfunction was not evident by examining mean scores alone. There are very few research studies that have applied the BRIEF in a pediatric stroke population. Two such studies represent work by Long and colleagues (2011a, 2011b). This research also documented significantly poorer performance in both hot and cool EFs in pediatric stroke participants relative to the normative population.

A major strength of the BRIEF as an EF assessment tool is its ecological validity. Primary caregivers are able to comment on EFs as they are overtly expressed in daily behaviours of the child. In contrast, EF laboratory tests are conducted in highly controlled environments that may lack similarity to real life task demands. In contrast to laboratory tests, real life tasks involve distracters, conflicting information, heightened emotionality, and potential for personal gain. Because accurate ratings involve good knowledge of the child's behavioural tendencies, the current study had primary caregivers complete the BRIEF questionnaire. Although there is potential for rater bias, the ecological validity of the BRIEF provided a strong incentive for the use of this measure. This study makes an important addition to the small quantity of existing BRIEF research on pediatric stroke.

### **Social-Emotional Behavioural Outcomes**

Stroke participants demonstrated significantly greater social-emotional behaviour deficits on several scales of the BASC-2. The Behavioral Symptoms Index is an overall indicator of behavioural problems. Relative to the control group, T-scores were significantly greater for the stroke group on the Behavioral Symptoms Index, which indicated more problems. On the primary scales, the stroke group demonstrated significantly more troubles in Atypicality,

Aggression, and Conduct Problems. Results indicated that stroke participants were more likely than control participants to engage in behaviours that are strange or odd, act aggressively towards others, and engage in rule-breaking behaviour. Initially, it was hypothesized that children with stroke would have significantly greater social troubles in comparison to typically developing children. However, statistically significant group differences were not found for the Social Skills scale or Withdrawal scale. Results suggested that stroke participants possess sufficient social skills and are not likely to avoid social situations. Effect sizes were in line with findings. Small effects were noted for Social Skills and Withdrawal, a medium effect was noted for Conduct Problems, and a large effect was noted for Atypicality and Aggression.

Despite higher incidence of aggression and rule breaking behaviour, children with stroke were still able to initiate positive social interactions, as indicated by the Social Skills scale. This may be due to the fact that problem behaviours did not reach levels of clinical significance on the BASC-2 since all T-scores were below 70. However, it is also important to consider the questions contained within the BASC-2, as this provides insight into the types of social interactions that are being quantified. An item analysis of the Social Skills scale indicated that this scale may not comprehensively represent the quality of peer relationships in children with stroke. For instance, children are rated more highly on Social Skills in the BASC-2 if parents indicate that they say “please and thank you”, “congratulate others”, and “offer compliments”. Thus, children can score highly if they follow pleasantries and adhere to the rules of courteous social interaction. Unfortunately, the scale does not address the formation, endurance, or quality of friendship bonds. Moreover, ratings on the BASC-2 tend to apply to parental observation in the home environment alone. This is problematic, given that social interaction may look quite different in a school context among peers. Overall, social results suggested that children with

stroke are aware of social rules and can use them sufficiently to convey a sense of respect.

However, we cannot rule out the presence of peer rejection or inappropriate social interactions with other children.

Accordingly, the poor social relations and peer-rejection documented in other pediatric stroke research (Gomes et al., 2012; Hurvitz et al., 2004; Trauner et al., 1996) were not corroborated in the current study. However, as reviewed, this may be due to the item content of the Social Skills scale. Future research studies examining social skills in children with stroke may want to implement different measures of social skills that are more sensitive to the nature of peer social relationships. A teacher questionnaire focusing on prosocial tendencies and peer problems would be advantageous (e.g. The Strengths and Difficulties Questionnaire; Goodman, 1997). Our social-emotional stroke group findings did support an elevation in issues of self-control, anger, and impulsivity, as was found by Trauner and colleagues (1996). In addition, prior pediatric stroke studies that have focused on social-emotional behaviour outcomes have also indicated that issues are moderate in severity. For instance, Gomes and associates (2012) found that children with a history of stroke display reduced prosocial tendencies, but problems were not severe and did not reach the level of difficulty that would be found in other pediatric brain injury populations. If social skills training were applied in pediatric stroke patients, it should encourage improved, more emotionally adaptive problem solving strategies that do not involve hostility or deception.

### **Academic Achievement Outcomes**

As predicted, the stroke group had significantly lower scores in Calculation, Math Fluency, and Spelling academic tests in comparison to the control group. Lower scores on the pencil and paper arithmetic tests represent reduced ability to perform mathematical computations



and reduced ability to quickly and accurately complete simple addition, subtraction, and multiplication questions. A significantly lower score in Spelling in the stroke group represents a lesser ability to properly spell orally presented words. Effect sizes were medium for Calculation and large for Math Fluency and Spelling. For the stroke group, mean standard scores in Calculation (86.53) and Math Fluency (85.00) were in the below average range, while the mean Spelling standard score (96.07) was in the average range of performance. Accordingly, it can be said that stroke group deficits were subtle for spelling ability and more profound for arithmetic. The large effect size observed for the Spelling comparison can be attributed to the above average performance of the control group, as their mean Spelling standard score was almost one standard deviation above the normative mean (113.6). The control group demonstrated average performance on math subtests; thus, significant group differences in math are a more accurate reflection of poor arithmetic ability among stroke participants. In prior research, pediatric stroke survivors exhibited reduced competency in both math and spelling (Allman & Scott, 2013; das Dores Rodrigues et al., 2011; Max et al., 2010; Sanders et al., 1997). Most studies report mean standard scores for the stroke group that are in the below average range (das Dores Rodrigues et al., 2011; Max et al., 2010; Sanders et al., 1997).

Proportional analyses provided information on impairment rates in each subject area. For the stroke group, 40% of participants demonstrated impairment in Calculation, 47.1% demonstrated impairment in Math Fluency, and 23.5% of stroke participants demonstrated impairment in Spelling. Proportional group comparisons for impairment rates between stroke and control groups were only significant for Math Fluency. The lack of significance for the Calculation comparison was due to the surprisingly large number of control participants that were underachieving in math. Overall, results indicate that arithmetic is a prominent area of

concern in children and youth with stroke. Calculation is a math test that involves increasing level of math skill as the test progresses. It involves addition, subtraction, multiplication, division, and combinations of these operations. It also introduces some trigonometric, geometric, logarithmic, and calculus operations as the test progresses. In contrast, Math Fluency is a much simpler test that only involves addition, subtraction, and multiplication. However the test is speeded and participants must perform as many problems as they can within three minutes. Low achievement in Math Fluency may indicate an underlying processing speed deficit in the stroke population. Stroke infarcts can damage the brain's white matter, which is directly responsible for the speed of transmission of nerve signals (Cardenas et al., 2011).

Overall, lower mean scores and highest impairment rates were seen in math subtest performance for the stroke group. The results of the current study converge with research on other childhood neurological disorders (e.g. TBI, multiple sclerosis, very low birth weight), which frequently cite greater impairment in the area of arithmetic (Barnes, Fletcher, & Ewing Cobbs, 2007; Taylor, Epsy, & Anderson, 2009; Till et al., 2011). Mathematical cognition is complex and often draws upon various brain regions and basic cognitive skills that can be adversely impacted by brain lesions. Math relies upon the understanding of numerical magnitude, visual spatial awareness of the number line, processing speed, and working memory for multi-step problems (Geary et al., 2007). Indeed, fMRI and DTI neuroimaging research have confirmed that math activates diverse regions across the cortex in its execution (Fehr, Code, & Herrmann, 2007; Rickard et al., 2000). A relationship between the volume of subcortical brain structures (e.g. nucleus accumbens, inferior longitudinal fasciculus) and math achievement has also been documented in children and young adults (Jung et al., 2014; van Eimeren, Niogi, McCandliss, Holloway, & Ansari, 2008). Accordingly, when cortical or subcortical stroke

occurs, there is an increased likelihood that brain injury will disrupt the ability to perform arithmetic in some capacity.

### **Relationship between EFs and Academic Achievement**

Support was found for the hypothesized association and predictive value of EFs on academic ability. Generally, math and spelling were most strongly related to metacognitive EF ability, as was demonstrated through Pearson's correlations between academic scales and the main indices of the BRIEF. Calculation and Spelling correlated strongly with Metacognition and Global (overall) executive abilities, while Math Fluency correlated moderately with only Metacognition. Spelling also correlated with the Behavioral Regulation Index. The lack of significant correlations for Math Fluency may relate to the simplistic nature of this math task which only involves addition, subtraction, and multiplication. The ability to quickly complete these basic problems under timed circumstances would depend more strongly on processing speed than complex numerical skill. In contrast, the Calculation test encompasses more complex, untimed, mathematical tasks (e.g. algebra) that would rely more strongly on Metacognitive EF skills.

Arithmetic is dependent upon EF in several respects. Research has shown that healthy children's math performance is related to their ability to plan and organize their problem solving approach, inhibit inappropriate responses, and keep working memory active in order to carry over numbers and keep information in mind for multi-step problems. In addition, children also must be able to evaluate new math strategies and switch their problem solving approach to a more appropriate one, if necessary (Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009; Bull & Scerif, 2001; Geary et al., 2007). These same metacognitive skills are presumably equally critical for arithmetic performance in children with stroke. The strong relationship between Spelling and

EF that was also found in the stroke group can be explained by several skills required to accurately and efficiently spell words. In order to spell, a child must organize and prioritize the order of letters, inhibit the tendency to only spell words as they sound, and activate working memory in order to simultaneously access the word's meaning, context, and letter order (since there are often different synonyms and homonyms in the English language). This logic converges with the results of a 2013 intervention study in which an EF and working memory training program improved the spelling ability of 45 third grade female students with spelling learning disability (Malekpour & Aghababaei, 2013). Furthermore, youth developmental research had shown that poor spellers have reduced working memory capacity in comparison to average readers (Malstadt, Hasselhorn, & Lehmann, 2012; Steinbrink & Klatte, 2008).

The majority of the working memory tasks from the WMTB-C did not correlate significantly with academic outcomes in the stroke group. This was surprising, seeing that working memory is a component of Metacognition of the BRIEF, and several strong relationships were detected using this scale. Only a single correlation of medium strength was detected between Word List Recall WMTB-C score and Spelling. Word List Recall measures the phonological loop component of working memory. Phonological working memory enables individuals to access and manipulate the sound units of language (Steinbrink & Klatte, 2008). Memory for phonological information is important for both spelling ability and reading ability; hence, the observed correlation is a sensible relationship. Other research has shown that specific deficits to phonological working memory result in poor outcomes for spelling in healthy children (Steinbrink & Klatte, 2008). The lack of significant relationships for the other working memory tasks, despite significant relationships for the BRIEF, may be due to the very nature of standardized clinical EF tasks. It is likely that the BRIEF parent questionnaire is more sensitive

to variations in EF as manifested in a child's overt behavioural choices and functioning. In contrast, standardized clinical tasks are performed in highly controlled laboratory environments with minimal distracters or conflicting information. These tasks may tap into core cognitive skill, but the actual overt expression of EF ability in the environment may be best measured by the BRIEF.

The Metacognition Index represents children's capacity to actively problem solve in a variety of contexts, and incorporates the ability to initiate, plan, organize, self-monitor, and sustain working memory. It was hypothesized that the Metacognition Index would most strongly relate to academic achievement since math and spelling presumably rely upon these "cool", cognitively-oriented problem solving skills. The correlational analyses confirmed this hypothesis. In addition, hierarchical linear regression confirmed the relational power of Metacognition in its ability to directly predict Calculation and Spelling scores in the stroke group. In stroke participants, the Metacognition score contributed unique variance to the prediction of Calculation and Spelling scores, even after accounting for the effects of intelligence. Metacognitive EF ability accounted for approximately 49% of the variability in Calculation and 35% of the variability in Spelling. This demonstrates a large effect that is consistent with previous studies documenting a significant relationship between EF, arithmetic, and literacy in healthy children (Bernier et al., 2010; Blair & Razza, 2007, Geary et al., 2007). To our knowledge, this is the first investigation of these relationships in youth with stroke.

Pearson correlations and regression analyses in the control group mostly yielded non-significant findings. Some working memory test battery scores significantly correlated with academic results (mainly Backward Digit Recall). However, remaining correlations with the BRIEF were not significant and Metacognition did not contribute unique variance to the

prediction of Calculation and Spelling scores in hierarchical linear regression analyses. The reason for the lack of significant findings in the control group is unknown since the same EF-academic relationships would be expected in healthy children. Notably, control group participants displayed less variability in BRIEF scores when compared to the stroke group's variability. Few control participants obtained high scores on the BRIEF, as most of their data-points were clustered beneath a T-score of 60 (i.e. few controls obtained clinically significant scores). It is possible that range restriction may have led to a reduction in the ability to detect and display a trend, even if present.

### **Relationship between EFs and Social-Emotional Functioning**

Support was found for the hypothesized association and predictive value of EFs on social-emotional behavioural functioning. Generally, behavioural symptoms were most strongly related to behavioural regulatory EF ability, which was expected given that behavioural regulatory EFs are responsible for the modulation of emotions and behavior via appropriate inhibitory control. Specifically, the Behavioral Regulation Index of the BRIEF encompasses the EFs of Shift, Emotional Control, and Inhibition. A child's mastery over behavioural regulatory EFs would be conducive towards appropriate responses and would presumably result in a decline in problem behaviour. Pearson correlations and hierarchical linear regression confirmed the hypothesized relationship in both the stroke group and the control group.

In the stroke group, BASC-2 scales strongly and significantly correlated with the main indices of the BRIEF, with the strongest correlations being with the Behavioral Regulation Index. Notably, the correlation coefficient between the Behavioral Regulation Index and the Behavioral Symptoms Index was .91. This relationship indicated that lower behavioural regulatory EF abilities in the stroke group were strongly associated with greater incidence of

behavioral problems including aggression, poor conduct (i.e. rule breaking, deception), hyperactivity, depression, and odd, disconnected behaviours. The standardized laboratory working memory subtests moderately correlated with Behavioral scales. Hierarchical linear regression analyses in the stroke group demonstrated that Behavioral Regulation EF score contributed unique variance to the prediction of Behavioral Symptoms score, even after accounting for the effects of intelligence. Specifically, Behavioral Regulation EF ability accounted for approximately 67% of the variability in Behavioral Symptoms score. This is a large effect and supports research by Gomes and colleagues (2012) that also investigated the relationship between EF and social behavioural outcomes in children with stroke. This study demonstrated that children with stroke have a reduced capacity to switch or alternate attention and that lower performance on Shifting Attention was associated with lower ratings on a peer relations scale and higher ratings on a peer problems scale. The research by Gomes et al. (2012) was the first published pediatric stroke study to establish a connection between EF processes and social-emotional behavioural competency within the peer context. However, to our knowledge, the current study is the first to establish this relationship using other “hot” emotional regulatory components of EF, given that the Behavioral Regulation Index of the BRIEF encompasses the Shift, Emotional Control, and Inhibit scales.

Similarly, the control group displayed a number of significant and strong correlations between BASC-2 scales and the main Indices of the BRIEF. Notably, the correlation between the Behavioral Regulation Index and the Behavioral Symptoms Index was .82. Thus, lower behavioural regulatory EF was also associated with an increase in behavioural problems in the control group. Conduct Problems of the BASC-2 did not display any significant correlations with EF scales, however. This may be due to range restriction, as data points clustered towards the

low end of the scale indicating few conduct problems in controls. In addition, there was slightly less score variability in Conduct Problems than on the other BASC-2 scales. Regardless, correlation coefficients would likely have been smaller with the Conduct Problems scale. This may indicate that in healthy children there are other factors, aside from EF, that strongly predict the presence of rule breaking behaviour and defiance. Potential variables include environmental factors, such as parental supervision, parent-child involvement, and the presence of positive role models (Loeber & Stouthamer-Loeber, 1986). These factors should also explain some of the outcome variability of Conduct Problems in the stroke group.

Hierarchical linear regression analyses in the control group also supported the predictive power of behavioural regulatory EF. Behavioral Regulation EF score contributed unique variance to the prediction of Behavioral Symptoms scores, even after accounting for the effects of intelligence. Specifically, control participants' Behavioral Regulation EF ability accounted for approximately 67% of their variability in Behavioral Symptoms score. This result is identical to what was observed in stroke participants and represents a very large effect. Other research has also supported the relationship between EF and social-emotional behavioural functioning in healthy children (Alloway, Gathercole, Kirkwood, & Elliott, 2009; Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009). For instance, a school study found that lower cool EF ability in school children was associated with reduced learning related classroom behaviours (Brock et al., 2009). Adverse behaviours encompassed increased disruptive behaviour, lower compliance, and reduced attention. The authors assert that positive classroom behaviours depend upon the child's ability to comply with teacher's directions without distraction (attention control EF), control impulses in favor of the required behaviour (inhibition EF), and activating a mental representation of rules and routines (working memory EF). Our study converged with these



findings, as we also found that behavioural outcomes strongly correlated with cool, metacognitive EF. However, the relationship was strongest with behavioural EF abilities. Interestingly, the Brock et al. (2009) study categorized inhibition as a cool EF ability, but the BRIEF measure subsumes inhibition under the “hot” Behavioural Regulation Index. This is because Inhibition is strongly tied to emotional regulation (Thomson, 1994). Hot EFs are traditionally defined as goal directed cognitive skills that are strongly involved in the regulation of affective and motivational processes (Hongwanishkul, Happaney, Lee, & Zelazo, 2005). In a comparison of hot and cool EFs in healthy children, deficits in hot EF have been reported to be more closely associated with impairments to social and emotional functioning (Hongwanishkul et al., 2005).

### **Mean Scores, Proportions, and Age at Stroke**

Overall, results indicated that stroke participants had subtle but statistically significant deficits across working memory and academic standardized tasks. The majority of mean scores for the stroke group were within the average to low average range of ability. In addition, behavioural EFs and social-emotional functioning were poorer in the stroke group than in controls, but most mean scores were not within the clinical range of impairment. Hence, stroke patients were within the broad range of average, but were compromised compared to healthy, typically developing children. If mean scores are taken as an indicator of functioning it would suggest that stroke participants are faring relatively well across most tested domains. However, when a distributional approach to analyses was taken, considerable variation in functioning was observed. In the stroke group, there was often a large range between the lowest and highest score and the majority of standard deviations were fairly large. Frequencies revealed that a considerable number of stroke participants were performing well below normative criteria; for

example, a working memory proportional analysis revealed that 31% of stroke participants attained Word List Recall standard scores of 85 or lower, while 0% of control participants fell in this “below average” range. Yet, there were also stroke participants that performed in the above average range. Across measures, scores tended to vary from three standard deviations below to two standard deviations above the mean. Results converge with many other pediatric stroke research studies which have described youth with stroke as a heterogeneous group that vary greatly in functioning (Ballantyne et al., 2008; Funnell & Pichford, 2010; Long et al. 2011a).

Considering the large amount of variability present in pediatric stroke participants, future research should continue to investigate factors that contribute to better or worse functional outcomes in a variety of cognitive and behavioural domains. This includes the effects of age at stroke, time since stroke, lesion location, lesion size, family structure, and educational opportunity. In the current study, the effects of age at stroke were examined. Age at stroke did not appear to relate to outcomes in EF, social-emotional, or academic domains, but few data points were available for childhood and adolescent stroke because the majority of participants incurred stroke during the perinatal period. Range restriction in the age at stroke variable likely affected the ability to examine relationships. Prior research has suggested a non-linear trend in the effects of age at stroke on various cognitive outcomes. For example, cross sectional studies have found poorer outcomes for math, spelling, reading, intelligence, and executive functions in youth with perinatal stroke (Ballantyne et al., 2008; Max et. al, 2010; Westmacott et al., 2010) and in youth who sustained stroke in late childhood and adolescence (Allman & Scott, 2013; Max et. al, 2010). Emerging research appears to suggest that normative neurocognitive profiles may be retained in early childhood stroke, between the ages of one and five, when the brain’s potential for functional reorganization after injury is greatest due to neural plasticity (Allman &

Scott, 2013). Given the importance of potential moderating variables in determining outcomes in pediatric stroke, Study 2 was dedicated to the investigation of age at stroke and lesion location variables.

## **STUDY 2: ARCHIVAL DATA**

### **Examination of the Effects of Age at Stroke and Lesion Location**

#### **Archival Study: Objectives and General Hypotheses**

To obtain additional information on important factors influencing academic achievement, archival data was utilized. This sub-study encompassed the analysis of math, reading, and spelling in children with a history of arterial ischemic stroke. Due to the larger number of participants in this database and a greater variability in the age and location of ischemia among stroke patients, lesion location analyses could be performed. Lesion location is a variable of interest because it has been established as an important moderating factor in cognitive outcome in prior studies. Hence, academic achievement analyses were divided into *cortical*, *subcortical*, or *combined* lesion location. Another major purpose of the present study was to establish a greater understanding of the developmental vulnerabilities and cognitive trajectory of children who have experienced stroke. Hence, analyses of the effects of age at stroke were conducted for the three academic achievement measures by categorizing youth according to *perinatal* (before 1 month), *early childhood* (1 month to 5 years) or *late childhood* (6 years to 14 years) stroke.

The following were the hypotheses for the archival project:

**Prediction 1.** It was hypothesized that children with a history of stroke would perform poorly on academic measures relative to normative standard scores. However, it was expected that the lowest scores would be in the domain of mathematics.

**Prediction 2.** It was hypothesized that children with a history of perinatal stroke (before

1 month) or stroke in late childhood (age 6-14) would perform more poorly on measures of academic achievement relative to children with early childhood stroke (1 month to 5 years).

**Prediction 3.** It was hypothesized that children with a history of stroke that have diffuse injury (i.e. injury to both cortical and subcortical brain regions) would perform more poorly on measures of academic achievement relative to children who only have a localized lesion to a cortical or subcortical area.

## **Method**

### **Participants**

The cognitive data of 103 children and youth with a history of unilateral arterial ischemic stroke were included in the present investigation. Participants selected from the database were between the ages of 4 to 20 years at the time of testing. The established inclusion and exclusion criteria were similar to that listed under study 1. Inclusion criteria consisted of the following: (1) a single AIS documented on MRI or CT; (2) arterial ischemic stroke before the age of 18 years; (3) at least 6 months post-stroke; and, (4) fluency in English. Exclusion criteria consisted of the following: (1) bilateral lesions; (2) multiple strokes; (3) seizure disorders; (4) preterm birth (less than 36 weeks gestation); (5) hypoxic-ischemic encephalopathy; (6) sickle cell disease; (7) psychosis; (8) moyo moyo disease (a rare cerebrovascular disorder caused by blocked arteries at the base of the brain); and, (9) any other neurological disorders (e.g., brain injury, malignancy, etc.). These criteria yielded a sample of 103 youth for academic data.

### **Procedure**

All data consisted of a retrospective participant sample of patients evaluated as part of a routine, post-stroke neuropsychological assessment at The Hospital for Sick Children. The children and youth selected from the database were evaluated between March 2002 and

November 2012. Parents had provided consent for their child's assessment results to be used for research purposes. Cognitive testing had been conducted at The Hospital for Sick Children where patients completed a battery of neuropsychological tests. Academic achievement data for math, spelling, and reading were extracted from the database for the current investigation. Participants had completed the Woodcock-Johnson Tests of Achievement-Third Edition (WJ-III; Woodcock et al., 2001) for academic achievement assessment. Parents completed a clinic questionnaire while their children were engaged in testing.

### **Measures**

*Clinic Questionnaire.* All caregivers were asked to complete a demographic questionnaire in order to collect information regarding participants' developmental and medical histories.

*WJ-III (Woodcock et al., 2001).* Children's academic abilities were assessed using the WJ-III test battery of achievement. Main subtests from the battery were administered to stroke patients. Performance on the Calculation, Spelling, and Letter-Word Identification subtests were selectively examined for the current study. The Calculation subtest is a paper and pencil test of math achievement which measures the participant's ability to perform mathematical computations, such as addition, subtraction, multiplication, and division. The test also includes some geometric, trigonometric, logarithmic, and calculus operations. Questions are arranged in order of difficulty, and the test taker's starting point is based on an estimate of their grade-based computational skill. The Spelling subtest is a measure of the ability to write orally presented words, which become increasingly difficult to spell. The test taker's starting point is based on an estimate of their grade-based spelling skill. Letter-Word Identification measures the test taker's word identification skills. The test is exclusively a measure of word reading, and the score is

based on number of words pronounced correctly. Each subtest is discontinued when the examinee obtains six consecutive scores of zero due to incorrect or incomplete responses. Standard scores ( $M=100$ ,  $SD=15$ ) and percentile ranks were computed as an indication of the child's performance relative to peers on each of the subtests.

Internal consistency reliability is high for individual tests (ranging from .80s to .90s) as well as for subject clusters (.90s). Test-retest reliability studies spanning 1 year intervals produced high median reliabilities (.80s to .90s). The achievement tests also have acceptable predictive validity, ranging within the .70s. In addition, the total achievement score correlates well with other achievement tests, thereby demonstrating convergent validity (Schrang, McGrew, & Woodcock).

### ***Neuroimaging Data.***

As a component of patient assessment at the Hospital for Sick Children, youth with a history of stroke underwent a clinical MRI or a CT scan for diagnostic and prognostic purposes. These data were used to selectively include children with unilateral arterial ischemic stroke in the study. Data on infarct size and location in the brain was also obtained and used to classify the stroke as: (1) *cortical* – cortical infarct with no subcortical involvement; (2) *subcortical* – infarct involving the basal ganglia or thalamus; or (3) *combined* – infarct involving cortical and subcortical regions. This information was used in the current study to divide academic achievement analyses according to ischemia location.

### **Statistical Analyses**

Firstly, data was analyzed to ensure that it met all assumptions of parametric tests. Homogeneity of variance across conditions was assessed using and Levene's Test. Normality was determined through the Shapiro-Wilk test, skewness values (values over +/- 2 are indicative

of non-normality), and by analyzing graphical representations of data distributions separated by condition. Holm's sequential Bonferroni procedure (Holm, 1979) was used to adjust for multiple comparisons by controlling the family-wise error rate. This approach controls for type I error inflation due to multiplicity, while maximizing power. Partial eta-squared values were computed as measures of effect size, where 0.01 = small, 0.06 = medium, 0.13 = large (Cohen, 1988). A one-tailed  $p$ -value was used for a statistical test result when the hypothesis was directional, and a two-tailed  $p$ -value was used for a statistical test result when the hypothesis was non-directional.

The participants' performance was compared to documented norms to determine the proportion of children performing below the 16th percentile in each of the academic measures (this is often recognized as the criterion for academic problems; Mather & Woodcock, 2001). Stroke participants were divided according to infarct location, which was classified as cortical, subcortical, or combined infarct. They were also divided according to age at stroke, with the three groups comprising perinatal stroke, early childhood stroke (1 month to 5 years), and late childhood stroke (6 years to 14 years). Three univariate, two-factor 3X3 ANOVAs were conducted to compare math, spelling, and word reading performance across the age at stroke and lesion location groups. A separate 3X3 ANOVA was conducted for each academic outcome variable. These two-factor ANOVAs allowed for the investigation of a potential interaction effect between age at stroke and lesion location. Significant univariate ANOVAs were followed-up with student  $t$ -tests. Finally, Pearson Correlations were conducted to examine age at stroke and time since stroke variables and their relationship to academic outcome.

## **Results**

### **Demographic and Clinical Characteristics**

The available demographic and clinical characteristics of stroke patients are presented in

Table 14. Chi-squared analyses for gender revealed that the proportion of male and female stroke participants did not significantly differ across lesion location groups [ $\chi^2(2) = 0.27, p = .872$ ] or age at stroke groups [ $\chi^2(2) = 1.78, p = .410$ ]. One-factor ANOVAs revealed that age at assessment did not significantly differ across lesion location groups [ $F(2,100) = 1.64, p = .199$ , partial eta squared = .03]. However, age at assessment significantly differed across age at stroke groups [ $F(2,100) = 25.85, p < .001$ , partial eta squared = .34]. Post-hoc tests revealed that there were significant group differences in age at assessment for comparisons between the perinatal stroke group and late childhood stroke group ( $p < .001$ ), and the early childhood stroke group and late childhood stroke group ( $p < .001$ ). The comparison between the perinatal stroke group and early childhood stroke group was not significant ( $p = 1.00$ ). As would be expected, younger age at stroke was associated with younger age at assessment.

**Table 14.** Characteristics of stroke participants for academic analysis, by age at stroke

	All Participants	Perinatal	1 mo-5y	6-14y
Total number	103	38	43	22
Males, no. (%)	60 (58.3%)	25 (65.8%)	22 (51.2%)	13 (59.1%)
Age at stroke, mean (SD)	3.24y (4.27)	0.002y (0.007)	2.51y (1.53)	9.97y (3.93)
Age at assessment, mean (SD)	10.92y (4.04)	9.34y (3.72)	10.02y (2.99)	15.38y (3.16)
Time since stroke, mean (SD)	7.74y (3.67)	9.34y (3.72)	7.51y (3.42)	5.42y (2.68)
Lesion Location				
Cortical	35	24	8	3
Subcortical	35	2	21	12
Combined	33	12	14	7

### Academic Achievement Outcomes by Age at Stroke and Lesion Location

Stroke patients' performance on Calculation, Spelling, and Letter-Word Identification subtests of the WJ-III were examined collectively for all participants (overall). Academic



performance was also examined according to age at stroke (perinatal, early childhood, or late childhood) and according to location of stroke in the brain (cortical, subcortical, or combined). Analyses did not correct for age since academic scores were already in standard scores (standardized according to age-normed achievement). Some missing data was noted, as some children were not administered the full WJ-III test battery due to time constraints. An examination of the database indicated that there were 86 values available for Calculation, 83 values for Spelling, and 93 values for Letter-Word Identification.

Overall, mean scores suggested that participants performed in the low average range on Calculation ( $M=86.7$ ) and within the average range on Spelling ( $M=97.2$ ) and Letter-Word Identification ( $M=97.5$ ). However a large amount of variability was apparent, as evidenced by large standard deviations. A proportional analysis was conducted to examine the quantity of stroke participants performing below normative criteria in math, spelling, and reading. Impairment was defined as a score that is one standard deviation or more below the normative mean. In standard scores, this is a score of 85 or lower. On the Calculation subtest, 32 (37.2%) stroke participants were in the impaired range. The proportion was slightly lower on the Spelling subtest, with 17 (20.5%) participants performing in the impaired range. On the Letter Word-Identification subtest, 13 (14.0%) participants were in the impaired range.

3X3 ANOVAs were conducted to examine the effects of 1) age at stroke, 2) lesion location, and 3) their potential interaction on academic outcomes. A separate 3x3 ANOVA was conducted for each academic test and the sequential Holm-Bonferroni procedure was used to correct for type I error inflation due to multiple ANOVA comparisons. Prior to analysis, academic data, divided by group, were examined for parametric assumption agreement. Normality was assessed via Shapiro-Wilk tests, skewness values, and graphical checks. Non-

normal distributions were observed in two groups: Calculation data for the early stroke group was negatively skewed, and Calculation data for the subcortical lesion group was negatively skewed. Normality was satisfactory for all other groups. Transformations could not be applied uniformly to groups, as distributions were not similarly shaped. Thus, normalizing one distribution would result in non-normality for others. ANOVA was retained for analyses since this parametric test tends to be robust to reasonable deviations from normality. Levene's test of variance homogeneity was non-significant for 3X3 ANOVAs, thereby indicating satisfaction of the variance assumption.

A two-factor 3X3 ANOVA was conducted with Calculation score entered as the dependent variable. The independent variables were age at stroke and lesion location. The ANOVA indicated that there was no significant interaction between age at stroke and lesion location [ $F(4,77) = 1.11, p = .178$ , partial eta squared = .05]. Further, there were no significant main effects for age at stroke [ $F(2,77) = 0.36, p = .349$ , partial eta squared = .01] or lesion location [ $F(2,77) = 1.39, p = .128$ , partial eta squared = .04]. All effect sizes were small.

A two-factor 3X3 ANOVA was conducted with Spelling score entered as the dependent variable. The independent variables were age at stroke and lesion location. The ANOVA indicated that there was no significant interaction between age at stroke and lesion location [ $F(4,74) = 1.24, p = .151$ , partial eta squared = .06]. The effect size for the interaction term was of medium strength. The main effect for age at stroke was not significant [ $F(2,74) = 0.06, p = .470$ , partial eta squared = .002], and the effect size was small. However, the main effect for lesion location was significant [ $F(2,74) = 3.75, p = .014$ , partial eta squared = .09] and the effect size was medium in strength. Post-hoc t-tests were conducted to examine where group differences existed for lesion location. Using the Bonferroni approach to adjust for multiple

comparisons, post-hoc analyses indicated a significant difference between the subcortical stroke group and combined lesion location stroke group ( $p = .013$ ), with the combined lesion group having the lower mean score. The mean score difference was almost 9 standard scores, which is a substantial difference. A significant group difference was also found between the cortical stroke group and the combined lesion location group ( $p = .029$ ), with the combined lesion group having the lower mean score. The mean score difference was 3.8 standard scores, which is a small difference. No significant differences were found between the cortical and subcortical stroke groups ( $p = .500$ ).

A two-factor 3X3 ANOVA was conducted with Letter-Word Identification score entered as the dependent variable. The independent variables were age at stroke and lesion location. The ANOVA indicated that there was no significant interaction between age at stroke and lesion location [ $F(4,84) = 0.24, p = .457$ , partial eta squared = .01]. The effect size for the interaction term was small. Further, the main effect for age at stroke was not significant [ $F(2,84) = 0.01, p = .498$ , partial eta squared = .00], and the effect size was extremely small. The main effect for lesion location was also not significant [ $F(2,84) = 2.91, p = .030$ , partial eta squared = .07], but the effect size was medium in strength. Table 15 presents the academic achievement standard scores of stroke patients, divided according to age at stroke. Table 16 presents the academic achievement standard scores of stroke patients, divided according to lesion location.

**Table 15.** Academic achievement scores in math, spelling, and reading, by age at stroke

	<b>All Participants</b>	<b>Perinatal</b>	<b>1 mo-5y</b>	<b>6-14y</b>
Calculation, mean (SD)	86.71 (24.42)	79.20 (27.21)	89.65 (23.49)	92.77 (18.87)
Spelling, mean (SD)	97.24 (13.51)	94.16 (16.54)	98.59 (11.78)	99.31 (11.54)
Letter-Word Identification, mean (SD)	97.49 (14.18)	93.00 (16.10)	99.89 (13.51)	99.31 (10.59)

Note: Subtest results are in standard scores

**Table 16.** Academic achievement scores in math, spelling, and reading, by lesion location

	<b>All Participants</b>	<b>Cortical</b>	<b>Subcortical</b>	<b>Combined</b>
Calculation, mean (SD)	86.71 (24.42)	84.22 (20.06)	93.00 (23.80)	81.75 (28.08)
Spelling, mean (SD)	97.24 (13.51)	96.57 (11.93)	101.61 (10.63)	92.79 (16.57)
Letter-Word Identification, mean (SD)	97.49 (14.18)	96.87 (13.10)	103.25 (11.33)	91.38 (15.90)

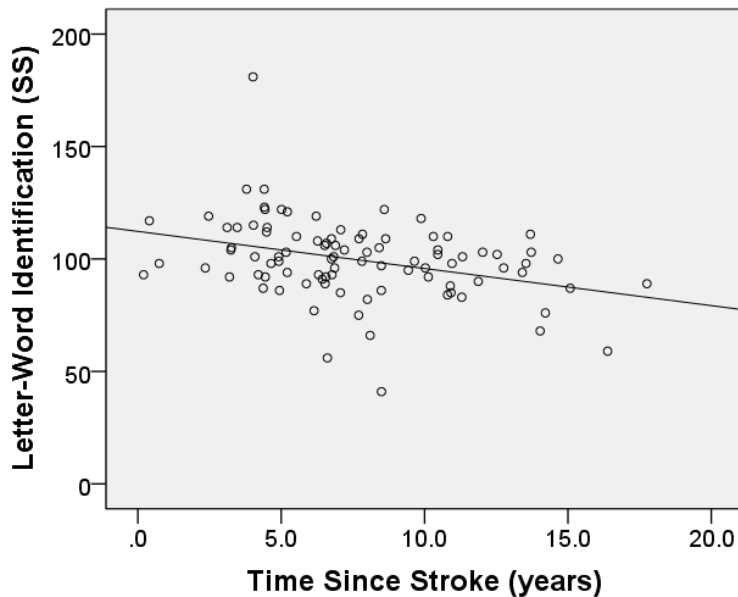
Note: Subtest results are in standard scores

Graphical displays were produced in order to visually examine any potential relationship between academic achievement and age at stroke. Age at stroke was entered as a continuous variable and was not divided into groups. Three scatter graphs were plotted with age at stroke on the x-axis and Calculation, Spelling, or Letter Word Identification on the y-axis. Data points were dispersed and did not follow any trend or relationship. Correlations and  $R^2$  coefficients were 0.0 for all graphs, which indicated that age at stroke did not account for any of the variation in academic outcome. The assumptions of linearity, independent errors, and homoscedasticity were met for all Pearson's correlations.

### **Time Since Stroke Analysis**

The relationship between time since stroke and academic ability was investigated through

Pearson correlation analyses. The assumptions of linearity, independent errors, and homoscedasticity were met for all Pearson's correlations. A linear trend was observed for time since stroke, where lower scores on Calculation, Spelling, and Letter-Word Identification were associated with greater time since stroke. Two-tailed Pearson correlations revealed significant relationships between time since stroke and Calculation scores [ $r = -.31$ ,  $R^2 = .10$ ,  $p = .004$ ], Spelling scores [ $r = -.24$ ,  $R^2 = .06$ ,  $p = .032$ ], and Letter-Word Identification scores [ $r = -.35$ ,  $R^2 = .12$ ,  $p = .001$ ]. Correlation coefficients were medium in strength for Calculation and Letter-Word Identification and small in strength for Spelling. Figure 5 displays a scatter plot of time since stroke in years (x-axis) graphed with Letter-Word Identification standard scores (y-axis) for all stroke participants.



**Figure 5.** Scatter plot depicting the relationship between time since stroke in years and Letter-Word Identification standard score (WJ-III) in all stroke participants

## **Discussion**

The main objective of study 2 was to examine the effects of age at stroke and lesion location on academic outcomes in children and youth with a history of arterial ischemic stroke. This objective was accomplished by analyzing a large, archival database of 103 stroke patients that were diversified in the location of their ischemia and the developmental stage in which they experienced stroke during childhood or adolescence. This study examined the math, spelling, and word reading abilities of the pediatric stroke patients by analyzing their WJ-III academic achievement data from the Calculation, Spelling, and Letter-Word Identification subtests. Comparisons were made among participants who experienced stroke during the perinatal period, early childhood (1 month-5 years), and late childhood (6-14 years). In addition, comparisons were made among participants with cortical, subcortical, and combined (i.e., cortical and subcortical) lesions. It was hypothesized that patients would perform poorly across academic areas and that poorest performance would be in arithmetic. It was also predicted that participants in the combined lesion group would have poorer academic outcomes relative to participants with stroke localized to only cortical or subcortical brain regions. In respect to age at stroke analyses, it was believed that those with early childhood stroke would have better academic outcomes relative to those with perinatal stroke or late stroke. The study also explored whether there was a potential interaction between age at stroke and lesion location variables.

### **Overall Academic Outcomes**

As expected, arithmetic was an area of concern in children with stroke, with overall mean Calculation standard score falling in the below average range (86.7). However, results did not confirm predictions for the other academic measures. Stroke patients performed in the average range on Spelling (97.2) and Letter-Word Identification (97.5). Further analyses revealed the

proportion of patients that were performing in the impaired range for each academic measure. On the Calculation subtest, 37.2% stroke participants were in the impaired range. The proportion was slightly lower on the Spelling subtest, with 20.5% of participants performing in the impaired range. On the Letter-Word Identification subtest, 14.0% of participants were in the impaired range. Results suggest that the majority of patients performed relatively well on the tests of literacy, although some individuals were struggling on these measures. Deficits were more apparent on the Calculation subtest, where both the overall mean and rate of impairment indicated more problems. These results confirm findings from study 1, which were remarkably similar.

### **Age at Stroke Analyses for Academic Achievement**

Across academic measures, scores were lowest for children who had perinatal stroke. Scores for early and late childhood stroke were similar and higher than perinatal stroke scores. Calculation outcomes were especially poor for the perinatal stroke group who attained a mean standard score that was in the borderline range of achievement (79.2). Across measures, academic achievement discrepancies between perinatal and childhood stroke ranged from a minimum of 4 to a maximum of 14 standard scores. Despite these differences, analyses for age at stroke were not significant for any of the academic measures. Thus, the score differences were visibly apparent and demonstrated a trend but did not reach a level of significance. This was likely due, in part, to large standard deviations which are factored into the ANOVA equations. The *F*-statistic is only significant when between-group variability exceeds within-group variability. The broad range of functioning observed amongst stroke participants converges with findings from Study 1.

Results did not support the hypothesis concerning non-linearity of age at stroke

outcomes. This hypothesis was derived from the extant literature, which suggests that poorest pediatric stroke outcomes are associated with perinatal stroke and stroke in late childhood or adolescence (Allman & Scott, 2013; Ballantyne et al., 2008; Max et al., 2010). This non-linear cognitive trend is presumably mediated by the processes of vulnerability and plasticity, where the vulnerable newborn brain is immature and in a rapid state of development and the adolescent brain is less changeable or “plastic.” Hence, some researchers believe that stroke in early childhood carries a protective neurocognitive effect due to optimal potential for functional reorganization (Allman & Scott, 2013). However some researchers have found that perinatal stroke bears poorest outcomes regardless, even when compared to early or late childhood stroke. This was the finding of Westmacott and colleagues (2010) when they compared intellectual abilities of children with perinatal stroke, stroke between the ages of 1 month to 5 years, and stroke between the ages of 6 to 16 years.

It is not known why the current results did not support any significant age at stroke finding (linear or non-linear). As previously mentioned, results supported a trend where low scores were associated with the youngest age at stroke (perinatal stroke); however, differences did not reach a level of significance, which may have been due to high within-subjects variability. Nevertheless, graphical analyses supported the quantitative findings, as they did not reveal any apparent age at stroke trend. Most of the existing age at stroke studies have been conducted on abilities other than academic skill, making it difficult to generalize to the area of school achievement. Intelligence and EFs tend to be the main focus of this research, and it is likely that different abilities will have different sensitive periods where brain injury will be most detrimental (Johnson & Munakata, 2005; Max et al., 2010).



### **Lesion Location Analyses for Academic Achievement**

Lesion location was found to be an important variable in determining Spelling outcome. Cortical and subcortical lesion groups significantly differed from the combined lesion location group, with the combined group having substantially lower scores on Spelling. The combined lesion stroke group also had lower scores on Calculation and Letter-Word Identification, but comparisons did not reach significance for these subtests. Results trended towards significance for Letter-Word Identification at  $p=.03$ , but failed to make the Holm-Bonferroni cutoff for multiple comparisons. The effect of lesion location on academic outcome has not been previously examined, but research by Westmacott et al. (2010) has established combined lesions as being more detrimental to intellectual outcomes than cortical or subcortical stroke alone. Such lesions tend to be larger and have increased potential of affecting important cognitive neural circuitry (Long et al., 2011b).

### **Analysis of Interaction Effects**

Study 2 did not find an interaction effect between age at stroke and lesion location. Few studies have examined the interaction of these variables in children with a history of stroke. Consequently, we could not hypothesize how one variable would relate to outcomes when modulated by the other. One such study, conducted by Westmacott et al., (2010) focused on how age at stroke and lesion location affect intellectual outcomes. Overall, perinatal stroke was associated with poorest outcomes regardless of lesion location, but some interaction effects were noted. The study found that the peak vulnerability period for children with subcortical stroke is during the perinatal stage. In contrast, children with cortical stroke demonstrated poorest outcomes in perceptual reasoning and overall intellectual ability when stroke occurred between the ages of one month to five years (Westmacott et al., 2010). These important findings

specifically relate to emerging intellectual skills in the infant and childhood developing brain. The current study failed to support such an interaction effect using academic achievement data.

### **Time Since Stroke**

Greater time since stroke was associated with lower scores on Calculation, Letter-Word Identification, and Spelling. This relationship was linear for all variables and of medium strength for math and word reading and of small strength for spelling ability. This result stands in contrast to a longitudinal research study which reported stability of academic deficits during the school years. In this study, youth with ischemic perinatal stroke were found to have significantly poorer performance in reading, spelling, and math. Although significant deficits were present, children's standard scores were stable over a three year time interval (Ballantyne et al., 2008). Since the current study examined the effect of time over a span of 18 years, it can be said that the time since stroke result of Study 2 is far more informative than studies that only examine children's academic performance over two or three years. Had the Ballantyne et al. (2008) school study used longer retest intervals, the researchers may have discovered a significant time since stroke effect. While Study 2 examines academic score trends over a longer time interval, it is also important to note that our study design was cross-sectional rather than longitudinal. Despite this limitation, our results appear to support the developmental arguments posed within prominent pediatric neuropsychology research literature that focuses on the long term effects of brain insult. Childhood traumatic brain injury studies frequently cite that brain injury may disrupt neural processes necessary for the attainment of future developmental milestones. Thus, deficits may not be immediately apparent and could emerge several years after the time of injury (Anderson et al., 2005). A longitudinal pediatric stroke study supports this paradigm. Researchers found that intellectual deficits in nonverbal reasoning, working memory, and processing speed emerged

from preschool age to school age in children with neonatal arterial ischemic stroke (Westmacott et al., 2009). Taken together, results emphasize the need for early cognitive and academic intervention efforts in pediatric stroke as deficits may be progressive and cumulative.

### **General Discussion**

Studies 1 and 2 converged in several respects and provided insight on important cognitive and behavioural outcomes in youth with a history of arterial ischemic stroke. Both studies indicated the presence of subtle deficits across the majority of tested domains. Relative to controls, children with stroke performed more poorly in verbal and non-verbal working memory, metacognitive EF, and behavioural regulatory EF. Math and spelling were also compromised, but impairment was mainly evident in the area of arithmetic. In children with stroke, heightened behavioural symptoms were observed in the areas of aggression, conduct problems, and atypicality. Moreover, results confirmed the predictive power of EF in its contributions to both academic achievement and social-emotional behavioural functioning. In addition, both studies revealed large standard deviations for the stroke group. Within-group variability suggests that there is a broad range of functioning among children with stroke, with some performing in the impaired range, while others score within the broad range of average. Children with a history of stroke appear to represent a heterogeneous group that cannot be characterized by an overall mean score. Pediatric stroke research should continue to look into important variables that may moderate cognitive outcomes in this group. Future research should also look into academic and cognitive trajectory over time to determine if deficits are stable or progressive. Archival study findings indicate that greater time since stroke is associated with lower academic achievement. Thus, deficits may be cumulative and are likely to become more apparent at a later stage in development. Lesion location and size are other important moderating variables in determining

the effects of stroke on academic outcome. Larger lesions affecting both cortical and subcortical regions were associated with reduced academic achievement in Spelling.

### **Limitations and Future Directions**

This research makes a unique contribution to our current knowledge regarding the neuropsychology of pediatric arterial ischemic stroke. Results heighten our understanding of behavioural EF in this population and its relationship with important academic and social-emotional outcomes. To assess these relationships, this study used well-established measures that are considered the gold standard in clinical assessment and practice. In addition, this research is one of the first studies to examine the effect of lesion location on academic outcomes. Despite these contributions, it is important to note the limitations inherent in the current study, as all research should be interpreted with care and veracity. For instance, it is pertinent to note methodological caveats, the limitations of generalizability, and how study design can be improved for future research.

This study was conducted on children with the arterial ischemic subtype of stroke. Consequently, results cannot be generalized to children with hemorrhagic stroke or stroke due to vascular anomalies such as sickle cell anemia or Moya Moya disease. Age limits of the participants also reduce applicability. Preschoolers and teenagers over the age of 14 were not included in the analyses of Study 1. Future developmental stroke research should include a wider age range of youth since this would assist in improving the generalizability of findings. Furthermore, the present research was cross-sectional rather than longitudinal, as data was collected at one time point from participants of varying ages. Since the studies did not follow participants over time, results may not provide definite information about cause and effect relationships. This is especially true for the time since stroke analyses. Further research could

longitudinally follow stroke participants throughout their school years and test them on the same measures at different points in time, ideally years apart. Furthermore, subsequent research should differentiate the effects of age at stroke, time since stroke, and age at assessment. This is an important future direction since these variables are all interrelated and may confound time since stroke results.

Although both standardized laboratory and parent report measures were used, both carry inherent shortcomings. Parent report is vulnerable to personal bias, and standardized clinical laboratory measures can be influenced by personal and environmental factors at the time of testing (i.e., exhaustion, time of day, lighting, rapport, anxiety level). Furthermore, laboratory testing occurs in highly controlled environments that lack resemblance to real life settings. Thus, both forms of tests can only provide an approximation of a child's true abilities. Another limitation relates to the methodological constraints of small sample sizes. Study 1 was exploratory and was characterized by a small number of participants (32 per group). As a result, there were not enough participants to perform age at stroke analyses or lesion location analyses divided by group. Small sample sizes in Study 1 also led to a lack of statistical power, which may have limited the ability to detect true group differences. Moreover, only a subset of stroke and control participants were administered academic achievement measures due to time constraints during neuropsychological testing. This further reduced power for academic achievement statistical analyses in Study 1. Although clinical research tends to be based on small sample sizes, 60 participants per group would be ideal for an adequately powered study. The stroke participants of the first study were not adequately diversified according to age at stroke, which also restricted analyses and the generalizability of findings. Most participants experienced stroke during the perinatal period due to naturally higher rates of pediatric stroke in early life.

For this reason, a second study was included which relied upon a large sample of archival data. This allowed the researcher to select more even proportions of children with childhood stroke.

In Study 1, several siblings of stroke participants were tested and served as control group participants. This enabled easy access to a control group that was similar to the stroke group in genetics, race, family background and other environmental variables such as socio-economic status (SES) and schooling. Despite the numerous advantages, some researchers express concerns about this practice since there may be subclinical symptoms in siblings of children with clinical disorders. Increased risk is present due to shared genetics and environment. For instance, it is possible, although unlikely, that the siblings of stroke patients had an undiagnosed vascular anomaly that could have affected learning, cognition, and development. If so, this may have acted to reduce the size of score differences between the clinical group and the control group. Another factor to take into consideration is the impact of environmental variables on EF development. Such variables were not taken into consideration in the current project. Positive family environment and parental involvement (i.e., scaffolding of children's learning) have been shown to result in better EF outcomes in youth (Bernier et al., 2010). In the current study, the majority of participants came from intact, two-parent homes that were relatively high in SES. This may have resulted in better EF outcome among both groups. Future research should examine cognitive, academic, and social-emotional outcomes in children from a variety of SES and parenting backgrounds.

### **Conclusion and Clinical Implications**

Overall, results suggest that pediatric stroke patients with diffuse lesions and reduced EF ability reflect a group that is at increased risk of poorest outcomes. Deficits to “cool” metacognitive EFs are strongly connected to lower academic achievement, and deficits to “hot”

behavioural regulatory EFs are strongly connected to social-emotional behavioural difficulties. Moreover, greater time since stroke may exacerbate academic difficulties. Findings have clinical value and can be used to assist in long term prognosis. Arithmetic achievement appears to be a particular area of concern for children with stroke as was indicated by below average standard scores and high rates of impairment. This is a concerning finding given that arithmetic is a core skill required for scholastic and occupational success. Mathematical thinking enables persons to comprehend number concepts, such as percentages, fractions, and ratios. It allows us to perform mental calculations and understand spatial relations. Each of these skills also factors into daily functioning; for instance mathematical skill is implemented when managing time, budgeting monetary resources, operating technology, and reading maps and calendars (Mazzocco, 2007). Thus, deficits to arithmetic skill may result in some issues with adaptive daily functioning and could reduce future career options in these youth.

Regarding social-emotional functioning, children with stroke did not appear to exhibit problems with social relationships; in addition, they did not exhibit heightened levels of withdrawn behaviors. Behavioural symptoms in patients with stroke appeared to be within the domains of aggression, atypicality, and conduct problems. Thus, children with stroke may display heightened levels of hostility, rule breaking, and odd behaviours that are disconnected from the environment. These types of behaviours are more likely to be seen in children with poor behavioral regulatory EF. Over time, behavioural symptoms may impair relationships and lead to poor adjustment in home and school environments (Crick & Dodge, 1994). Together, findings suggest that there is great need for pediatric stroke intervention efforts targeting EFs, as these abilities support important skills (i.e., math, spelling, adaptive social behaviour) that are necessary for functioning in school and everyday life.

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