Mathematical Ability of Autistic Youth: What Best Explains the Heterogeneity?

by

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Abstract

Background: Autistic individuals are often stereotyped as gifted mathematicians and, as a result, autistic traits and behaviours are generally believed to lead to exceptional mathematical ability. Much of society's collective understanding of autism is based on media representations, which often foster unrealistic expectations of their skills by families and teachers, leading to additional barriers for autistic students (Draaisma, 2009). This is concerning given that autistic students are more likely to have a mathematics learning disability (LD) compared to mathematical giftedness (Oswald et al., 2016). Autistic students may struggle in the upper grades when mathematics relies more heavily upon abstract reasoning and becomes cognitively complex (Barnett & Cleary, 2019). In fact, studies have found several variables that influence the mathematics achievement of autistic students such as language and executive function (EF) skills (Bullen et al., 2020; Chen et al., 2019; Polo-Blanco et al., 2022; St. John et al., 2018).

Objectives: Across two mathematics composites (Basic Concepts and Applications), I explored the relative proportions of low– and high–achieving (± 1 *SD* of the norm) autistic youth compared to the expected rates in the general population. Second, I investigated the relative contributions of fluid reasoning (G*f*), expressive language, and EF on the Basic Concepts composite.

Methods & Results: 33 autistic youth (aged 5–16 years) completed measures of mathematical ability (KeyMath-3 DA^{CDN}), fluid reasoning (*Gf*; Raven's Progressive Matrices or Leiter-3), expressive language (CELF-5), EF (BRIEF2), and autistic traits (SRS-2). Chi–squared tests for Basic Concepts ($p < .01$, $\varphi = .54$) and Applications ($p < .05$, $\varphi = .47$) revealed a significantly higher proportion of autistic youth who were low–achieving (21.21% and 25%, respectively) and/or high–achieving (33.33% and 28.57%, respectively) in my sample compared to the expected rates in the general population (approximately 15%). Using the Basic Concepts composite, a hierarchical regression analysis revealed that G*f* was the strongest predictor of mathematical ability accounting for 53% of the model variance ($\beta = .54$, $p < .001$). Furthermore, expressive language accounted for 8% of the model variance ($\beta = .33$, $p < .05$) and EF accounted for 5% of the model variance ($\beta = -.23$, $p < .05$).

Conclusions: My findings challenge prevailing stereotypes of an autistic advantage in mathematics and emphasize the need to understand the unique strengths and needs of each autistic student. My study highlights the importance of promoting more accurate representations of the distribution of mathematical ability among autistic youth. While studies have consistently reported that G*f* is associated with mathematics achievement in non–autistic individuals (Cormier et al., 2017), this study found that G*f* is a large and important predictor of autistic students' mathematical ability. My findings regarding the importance of expressive language and EF skills were less clear but both were significant predictors of mathematical ability. Future researchers should consider a) exploring the relationships among these predictors with a larger sample; b) using a holistic measure of language ability to quantify how specific language subskills may be related to different mathematical abilities; and c) incorporating a direct measure of EF that will provide an objective and reliable way to quantify EF. In sum, this study highlights the importance of promoting more accurate representations of the broad range of mathematical ability across autistic youth. Understanding which variables are most strongly related to mathematics achievement among autistic students can help researchers, clinicians, and educators develop effective interventions and strategies to ensure autistic students receive the necessary resources and support to succeed in mathematics.

Preface

This is an original work by Léonie Hoveling. The research conducted for this thesis was supervised by Dr. Heather M. Brown at the University of Alberta. This thesis represents part of a broader research project developed by Dr. Heather M. Brown. Given that this thesis uses secondary data, I developed the hypotheses, reviewed the literature specific to the research questions of interest, analyzed the data, and conducted statistical analyses described herein. The study was approved before data collection commenced by the University of Alberta Research Ethics Board, Project Name “Developing a Model of Mathematical Ability for Children with Autism Spectrum Disorders”, No. Pro00058795, April 20th, 2016.

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Introduction

Context of Problem

Much of society's collective understanding of Autism Spectrum Disorder (hereafter, autism) is based on media representations (i.e., books, movies, and TV series; Draaisma, 2009). Autistic individuals are often portrayed as gifted mathematicians—like the socially inept physicist Sheldon Cooper from the TV series *The Big Bang Theory* (Lorre et al., 2007–2019) and Raymond Babbitt from the movie *Rain Man* (Levinson, 1988). Such stereotypes perpetuate beliefs that all autistic people have similar traits and behaviours and that these lead to exceptional mathematics achievement. While autistic individuals are often found in science, technology, engineering, or mathematics (STEM) related careers (Oswald et al., 2016), this bias may nevertheless foster unrealistic expectations by families and teachers by expecting autistic students to demonstrate savant mathematical abilities.

Researchers currently have difficulty explaining the differences in mathematical abilities among autistic students. There is uncertainty regarding whether all autistic students possess similar mathematical strengths and weaknesses, or if these strengths and weaknesses vary among different subgroups of autistic students. Although some studies have attempted to classify autistics into subgroups based on their mathematical profiles (Chen et al., 2019; Wei et al., 2015), we are only beginning to explore these questions. The existence of diverse mathematical skills among autistic students undeniably challenges common stereotypes linked to autism. Furthermore, the importance of academic achievement for future success is well-established, and there is a clear association between the two (Nasamran et al., 2017). In the case of autistic individuals, their educational and employment outcomes are heavily influenced by their academic performance (Migliore et al., 2012). Considering this, it is crucial to gain a comprehensive understanding of the range of mathematical abilities among autistic youth and identify the variables that predict their mathematics performance. By exploring the rates of mathematical strengths and weaknesses in autistic youth, I aimed to better describe the heterogeneity of mathematical skills in this population and address societal misrepresentations, determine which cognitive characteristics predict mathematical ability, and provide recommendations for supporting this academic area of autistic youth.

Defining Autism According to the Pathology Paradigm

Autism is a well-known, heritable, and variable neurodevelopmental condition where the brain processes information in ways that result in lifelong differences in communication and behaviours (Lord et al., 2020). Our conceptual understanding of autism began with the work of Dr. Leo Kanner and Dr. Hans Asperger in the 1940s. Kanner's (1971) research—based on case studies—conceptualized autism as a series of deficits. More specifically, Kanner (1971) wrote that autistic children had an innate inability "…to relate themselves to people and situations in the ordinary way"; "an anxiously obsessive desire for the preservation of sameness"; and "autistic disturbances of affect contact" (p. 140). Asperger also mentioned similar deficits in his work suggesting autistic individuals demonstrated limited eye contact, repetitive movements, and social difficulties (Fletcher-Watson & Happé, 2019).

Since then, research and social beliefs on autism have significantly evolved and will continue to do so (Fletcher-Watson & Happé, 2019; Volkmar & McPartland, 2014). The *Diagnostic and Statistical Manual of Mental Disorders Fifth Edition* (DSM-5; American Psychiatric Association [APA], 2013) has a single category for autism, titled Autism Spectrum Disorder. For a child to receive an autism diagnosis using the DSM-5 criteria, the child must show differences in two main domains: a) social communication and relationships and b) restricted, repetitive behaviours and interests (RRBIs). These lifelong traits must be present in the child’s early years across multiple environments (DSM-5; APA, 2013; Fletcher-Watson & Happé, 2019). As well, autistic individuals experience sensory processing differences (Fletcher-Watson & Happé, 2019). However, sensory over- and under-sensitivity can vary within a single child and across children depending on individualized sensory preferences and the child’s current environmental situation (Samson et al., 2014; Weiss et al., 2014). In some circumstances, sensory stimuli can be overwhelming and aversive, while other sensory stimuli may provide the child with comfort.

Since its identification, autism has been understood through a deficit-based lens, concerned with normalizing and eliminating atypical development (Kapp et al., 2013). Most often, intervention targets differences in communication (from learning to communicate to connecting with others), emotional dysregulation, the reduction of repetitive behaviours, and broadening interests (Fletcher-Watson & Happé, 2019). Scientists working from this paradigm have tended to focus on defining autism by its deficits, which promoted scientific inquiry into the etiology of autism, reducing traits through interventions, and requiring autistic children to conform to neurotypical[1] societal norms (Fletcher-Watson & Happé, 2019; Walker, 2012). By seeking to explain biological differences between autistic and non-autistic individuals, the focus shifts from supporting autistic students’ quality of life, educational outcomes, and strengths to treatment (Fletcher-Watson & Happé, 2019; Kapp, 2019; Robertson, 2010). This pathology paradigm has received a great amount of criticism from autistic and non-autistic community

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[1] Walker (2012) defines the term neurotypical as individuals with dominant or ‘normal’ neurological processes who subsume a privileged position in society.

members due to its pejorative belief in ‘fixing’ the individual (Bottema-Beutel et al., 2021; Yergeau, 2018).

Defining Autism According to the Neurodiversity Paradigm

Considering a new perspective and growing empirical and community data, academics, autistics, and advocates (such as Dwyer [2022]) are reframing the way autism is understood and conceptualized (Fletcher-Watson & Happé, 2019). Proponents of the neurodiversity paradigm suggest diversity in human minds is natural, healthy, and valuable (Walker, 2012). At the same time, autistic individuals are more commonly joining the conversation on how to best empower autistic youth and adults, enhance rights, and promote their overall quality of life (Brown et al., 2022).

Contrary to the pathology model is the social model of disability which suggests that a person’s disability results “from society’s responses to individuals’ impairments” (Dwyer, 2022, p. 75). Proponents of the social model believe that the experience of disability stems from barriers in one’s environment that create limitations rather than being solely attributed to their individual differences (Oliver, 2013). Furthermore, this model proposes that societal perceptions and judgments need to change rather than changing the individual who experiences disability (Retief & Letsosa, 2018). This paradigm shift implies autism is merely a ‘different form of normal’ or diversity of the human condition (Subramanyam et al., 2019). Nevertheless, this model also has its limitations such that even if societal inclusion was addressed, some autistic individuals may still experience challenges because of their traits associated with autism (Ballou, 2018). Dwyer (2022) provided the example that if an autistic individual has executive function (EF) weaknesses, they might still experience EF difficulties in their daily life regardless of what supports are in place for them.

More recently, researchers have begun to move away from both the pathology paradigm and the pure social model of disability to adopt an interactionist model. To conceptualize disability, the interactionist model posits that we should seek to understand the interaction between a person's environment and their own characteristics—an interactionist neurodiversity framework (Dwyer, 2022). The fundamental belief is that a person's experience of disability comes from the interaction between individual traits (i.e., sensory processing differences or passionate interests) and how these characteristics interact with their environment (Dwyer, 2022). For example, in loud and noisy classrooms, the uncontrollable negative sensory stimuli (e.g., bright lights and loud sounds) can cause significant distress in autistic individuals; however, in a quieter and more supportive environment, the autistic person may not experience their sensory differences as disabling. Similarly, passionate interests coupled with innate talent (e.g., technological aptitude) might be viewed solely as a strength if one's interest ensured that as an employee, they used their commitment and expertise to make many important breakthroughs in their chosen field. Proponents of the neurodiversity paradigm suggest diversity in human minds is natural, healthy, and valuable (Walker, 2012). The neurodiversity movement has pushed clinicians and researchers to look beyond the autistic 'triad of impairments' (i.e., social, imagination, and communication; Wing & Gould, 1979). Proponents of this movement, including autistic self-advocates, celebrate the differences and diversity between individual minds (Dwyer, 2022), directing the conversation to one of inclusivity.

A second change in our conceptualization of autism relates to the notion of a linear autism spectrum where autistic individuals are often placed in discrete categories ranging from low- to high-functioning. Recent developments suggest viewing autism as a multidimensional constellation with 'complex interacting domains' (Fletcher-Watson & Happé, 2019). For example, autistic individuals may present passionate interests or expertise in an area that non-autistics find unusual (Lord et al., 2020; see also Bottema-Beutel et al., 2021). However, due to autism's heterogeneity, traits, cognitive abilities, and behaviours displayed within and between individuals vary considerably (Chen et al., 2019; Georgiades et al., 2013; Hyman et al., 2020). In a review, Kapp (2018) described autism as a "cloudy constellation of uneven skills" (p. 364), suggesting that one's performance is dependent on many contextual factors such as time, environment, social support, and individual variability.

Language in the Autism Field

There is an ongoing debate concerning the language used to describe autistic individuals, which involves many perspectives from different stakeholders (Vivanti, 2020). Both person-first (e.g., 'person with autism') and identity-first (e.g., 'autistic individual') language are advised by the American Psychological Association (2020). Proponents of identity-first (e.g., 'autistic individual') language suggest that person-first language may lead individuals to believe something is wrong with having an autism diagnosis, "potentially leading to an internalization of inferiority for those who receive the diagnosis" (Vivanti, 2020, p. 691). Many who adopt a neurodiversity-aligned perspective believe that a person's differences (e.g., autistic traits) are integral to who they are (Kapp et al., 2013; Kenny et al., 2016). While identity-first language is preferred by some autistic individuals and journals, there is currently no consensus in the autistic community about which type of language should be used (Bury et al., 2020). Nevertheless, I have chosen to primarily use identity-first language in this paper to be consistent with the neurodiversity perspective.

Prevalence

The Centre for Disease and Control (2023) in the United States mostly recently reported that approximately 1 in 36 children are autistic. According to the most recent Canadian data from 2019, approximately 1 in 50 (or 2%) of Canadian children and adolescents are diagnosed with autism (Public Health Agency of Canada, 2022). There were 5.7 million elementary and secondary students in Canada as of 2019/2020 (Statistics Canada, 2021) of which 766,280 reside in Alberta (Government of Alberta). This suggests there are approximately 14,896 autistic elementary and secondary students in Alberta.

There are a variety of factors that may influence autism prevalence rates: First, researchers have reported that prevalence rates can vary due to the definition used (i.e., diagnostic criteria and age range; Brugha et al., 2011; Chiarotti & Venerosi, 2020; Saemundsen et al., 2013). Second, differing worldviews and cultural / ethnic impacts on the behaviour traits associated with autism may influence its definition and prevalence (e.g., varying norms of social interaction; APA, 2013; Chiarotti & Venerosi, 2020). Third, due to the highly variable nature of autism (Chen et al., 2019; Hyman et al., 2020; Kapp, 2018), there is a broad range of traits expressed depending on the child's age and developmental stage, thus the likelihood of receiving a diagnosis varies (Volkmar & McPartland, 2014). For example, environmental factors may impact how disabling the child (and their support system) experiences their autistic traits at any given time. Fourth, many autistic individuals without an intellectual disability (WoID; Full-Scale Intelligence Quotient [FSIQ] standard score [SS] > 70) report that they often camouflage or mask their autistic characteristics and hide social differences to blend in non-autistic social environments (Cook et al., 2021; see also Hull et al., 2017; Lawson, 2020). While autism is more commonly diagnosed in boys than girls (Lord et al., 2020), this may be because girls are more likely to have their autism overlooked and/or misdiagnosed—potentially due to camouflaging—thus leading to high rates of missed or late autism diagnosis (DSM-5, 2013; Hull et al., 2020; Loomes et al., 2017). To further complicate matters, co-occurring conditions, such as internalizing difficulties (e.g., depression, anxiety, and self-injurious behaviours) as well as learning disabilities (Fletcher-Watson & Happé, 2019) are common among autistic people (Lord et al., 2020). As a result, the attention given to their mental health condition may overshadow any neurodivergence that could contribute to the development of these mental health concerns, potentially impacting prevalence rates. Though various factors can impact prevalence rates, it is irrefutable that the increased rates of autism (Canadian Academy of Health Sciences, 2022; Happé et al., 2016) require a shift in societal understanding to adopt inclusive policies that encourage autistics to thrive alongside non-autistics. With the increasing prevalence of autism over the decades, there is a great need for autism research to inform future research, policy, and public education.

Literature Review

Defining Giftedness and Learning Disability

To be able to discuss the rates of mathematical strengths and weaknesses among the autistic youth in my study, it is necessary to first consider the expected rates of mathematical giftedness and learning disabilities (LD) in the general population. However, this is difficult for several reasons. The construct of giftedness has no universally agreed upon definition, thus there are varying conceptual definitions (Burger-Veltmeijer et al., 2011; McBee & Makel, 2019). For example, the Gifted Children's Association of BC (2020) described gifted children as above age-equivalent peers in one or more abilities, whereas Alberta Education states that gifted students must demonstrate exceptional performance across several abilities in one or more disciplines and perform at or above the 98th percentile on an intelligence quotient (IQ) measure (Calgary Board of Education, 2022). In Canada and the United States, psychologists often use measures of academic achievement and cognitive ability as criteria for determining giftedness (DDSB Gifted Program; Gifted Children's Association of BC). Given that there is no universal definition used for identification, the rates of giftedness among students varies. In 1993, 21 states in the United States reported that less than 5% of students were gifted, yet four other states reported greater than 10% of their students were gifted (U.S. Department of Education, 1993). Furthermore, rates of giftedness vary depending on the IQ cut-off score used, ranging from 1% (at an IQ cut-off of 135) to 15–20% (at an IQ cut-off of approximately 115; Pfeiffer, 2002; see also McBee & Makel, 2019). Without a clear threshold that differentiates exceptional from above-average abilities, giftedness prevalence rates remain unclear (Pfeiffer, 2002).

Like giftedness, a learning disability (LD) has no precise definition that is universally accepted, and researchers have historically used inconsistent definitions (Maddocks, 2018). However, most agree that LDs affect one's organization, retention, and acquisition of information in reading, writing, and/or mathematics (Learning Disabilities Association of Canada, 2021). An LD traditionally described a child who was performing significantly lower than expected in a core academic domain given their cognitive abilities (as measured by an IQ test). Similarly, Maddocks (2018) reported schools often view an LD as a child who is "… scoring one standard deviation or more below the mean" (p. 177) compared to their same-age peers. Maddocks (2018) also suggests that an LD should be viewed in relative terms such that if a gifted child is performing lower than expected based on their "cognitive abilities or academic talents" (p. 177), they may be identified. Researchers and clinicians originally differentiated LDs from intellectual disabilities (ID) by broadly defining an ID as a child who scored two or more standard deviations below the mean on an IQ test along with significant difficulties in adaptive functioning (DSM-5, 2013). While students with LDs demonstrate significant difficulties in one or more academic domains, these students usually have average or above average FSIQ scores (i.e., FSIQ > 70; Moll et al., 2014). LD rates in the general population can range from 5 to 15% (Margolis et al., 2020; DSM-5, 2013; Learning Disabilities Association of Ontario, 2018; Shalev, 2007). Rates of a specific learning disorder (SLD) in mathematics in children in the general population are around 3–7% (DSM-5, 2013; Geary, 2011; Shalev, 2007). In one of the few studies to address this question directly among autistic youth Mayes and Calhoun (2008) reported that 23% of autistic children WoID ($N = 54$; aged 6–14 years) met diagnostic criteria for a mathematics SLD (more examples are given below).

Mathematical Abilities of the Autistic Population

Many students find mathematics one of their most challenging subjects (Siregar et al., 2020). This is especially true for students with higher support needs. In the sole, albeit dated meta–analysis of 18 studies, Chiang and Lin (2007) reported a range of mathematical ability (i.e., arithmetic and problem solving) in 837 autistic individuals (aged 3 to 51 years); the majority showed average mathematical skills, while some demonstrated mathematical weaknesses and others, giftedness.

More recently, Wei and colleagues (2015) explored the mathematics achievement profiles of 130 autistic children (WoID; aged 6–9 years) and found four distinct subgroups: 1) Higher-achieving, 2) hyperlexia (i.e., having exceptional word reading skills in contrast to their reading comprehension and is discrepant from their IQ), 3) hypercalculia (i.e., having exceptional arithmetic skills that are discrepant from their IQ; Jones et al., 2009), and 4) lower–achieving. Researchers found significant differences in overall achievement scores between the high–achieving and hyperlexia subgroups compared to the hypercalculia or lower–achieving subgroups. These findings clearly highlight the vast heterogeneity within the autistic population. The researchers also re–evaluated these subgroups, one year later and again three years later, reporting that the relationship between these subgroups changed over time. For example, the hypercalculia group had significantly weaker calculation skills in comparison to their previous performance over time, suggesting these students lost their mathematics advantage. These results may suggest that the mathematical skills and profiles of autistic children may not be static but can change as they develop.

Similarly, the results of Chen and colleagues (2019) give another example of the heterogeneity of mathematics achievement, specifically in boys. They found that their autistic sample's (*N* = 114; aged 7–12 years) mathematics and reading standardized scores fell within the average range. However, when looking at the variability within the autistic group, they clearly identified two subgroups—low– and high–achieving. The low-achieving subgroup tended to score lower on numerical operations, mathematical reasoning, word reading, and reading comprehension compared to the high–achieving subgroup. Furthermore, the low–achieving subgroup had lower scores across both mathematics (numerical operations and mathematical reasoning) and language (word reading and reading comprehension) domains, opposite to that of the high–achieving group. These findings echo the variability found in Chiang and Lin's (2007) meta–analysis. The available evidence on the mathematical abilities of autistic individuals is notably limited, and the research conducted thus far offers mixed findings on the mathematics profiles among autistic students (Peklari, 2019).

Despite these scientific results, a common misconception is that mathematical giftedness and autism are linked. This link was initially emphasized by the Baron–Cohen and his proposal that autistics have exceptional systemizing skills (Baron–Cohen et al, 2007). That is, they have strong cognitive processes (e.g., G*f*) and an innate drive to recognize patterns and generate underlying rules to solve problems. Ultimately, gifted autistics seek to understand how a system works and predict what it will do (Baron–Cohen & Lombardo, 2022). Baron–Cohen hypothesized that this talent may explain why autistics are disproportionately represented among talented mathematicians (Baron–Cohen et al., 2007; Baron–Cohen & Lombardo, 2022). Contrary to the prevailing stereotypes surrounding autism and giftedness, it is important to note that only 3% of autistic individuals are recognized as intellectually gifted (Charman et al., 2011; Karnes & Shaunessy, 2004). For preschool–aged autistic children with average to slightly above average IQs, some studies have found their early mathematical skills tend to be comparable or above-average, compared to their non–autistic peers (Iuculano et al., 2014; Titeca et al., 2017; Troyb et al., 2014). Some have attributed such findings to autistic children's inherent strengths in the rote memorization of math facts (Chiang & Lin, 2007; Iuculano et al., 2014). In a study with 18 autistic and 18 non–autistic elementary children, Iuculano and colleagues (2014) reported that the autistic children "showed greater reliance on sophisticated analytic strategies when solving single–digit addition problems … by breaking them into easier problems" (e.g., decomposition strategies rather than finger counting; p. 228) and stronger numerical operations skills (Hedges' $g = .88$) compared to the non–autistic children (see also Devenish et al., 2022). The children's strong algorithmic thinking may be due to their intrinsic ability to focus on the details of an equation.

Though some of the previous literature proposes a tendency toward the development of mathematical strengths in autistic youth, other studies indicate that some have significant challenges mastering mathematical concepts and skills. In fact, several recent studies have shown that mathematical weaknesses may be more common than mathematical strengths in autistic youth (Bullen et al., 2020; Keen et al., 2016; Oswald et al., 2016; Titeca et al., 2015). Oswald and colleagues (2016) found that 5.5 times as many autistic students had a mathematics SLD (22%) compared to mathematical giftedness (4%). Other researchers have reported that between 17% and 40% of autistic children (WoID) exhibited significantly lower mathematics proficiency (i.e., arithmetic and basic number skills) compared to what would be expected based on their IQ (i.e., IQ/FSIQ within one standard deviation of the population mean; Estes et al., 2011; Mayes & Calhoun, 2008). Similarly, a longitudinal study of 77 school–age autistic students WoID (M = 11.38 years, SD = 2.20), showed that the overall mean calculation and mathematical problem-solving scores were lower for autistic compared to non–autistic peers (n = 43) at time point one and these means "remained lower over [all] subsequent time points" (Bullen et al., 2020, p. 4472). In another study with 121 autistic children, researchers found that first graders (aged 6–7 years) demonstrated significantly below average scores on procedural calculation (i.e., computation) tests compared to age–adequate mathematical norms, however, this finding was not significant in higher grades (Titeca et al., 2015). Based on these findings, it is clear there is variability in mathematics achievement among autistic individuals, with several studies highlighting autistics' difficulties. Such results contradict the prevailing notion of mathematical talent among autistics. My study sought to add to the existing literature by exploring the proportions of low– and high–achieving autistic youth WoID in mathematics. Yet, these findings also beg the question: What explains this variability?

While some researchers have sought to understand the heterogeneity of mathematical abilities by grouping autistic individuals based on patterns of achievement (Chen et al., 2019; Estes et al., 2011; Jones et al., 2009; Wei et al., 2015), others have focused on identifying the relationships between cognitive characteristics and mathematical ability (Assouline et al., 2012; Bae et al., 2015; Miller et al., 2017; Oswald et al., 2016). Assouline and colleagues (2012) found that gifted autistic students with strong working memory[2] (WM), processing speed (PSI), and fine motor skills were more likely to also be strong in mathematics. Other studies demonstrated that general mathematical ability is most strongly predicted by fluid reasoning (G*f*; defined below) in non–autistic populations (Cormier et al., 2017; Green et al., 2017) and in some studies of autistic populations (Oswald et al., 2016). In fact, G*f* was one of three broad cognitive abilities related to arithmetic and problem–solving across all ages (McGrew & Wendling, 2010). Furthermore, McGrew and Wendling (2010) found that G*f* consistently predicted future mathematical ability beyond general intelligence (defined below) and understanding complex, abstract language. These challenges may lead to difficulties in mastering problem–solving skills, especially in the junior and intermediate grades as mathematics becomes more cognitively complex (Barnett & Cleary, 2019). In the following sections, I define G*f*, language, and EF and explore research related to each of these predictors in both non–autistic and autistic populations.

Predictors of Mathematical Ability in Children and Youth

Fluid Reasoning

Fluid reasoning (G*f*)—also known as fluid intelligence or nonverbal intelligence (NVIQ; Otero, 2017)—is the ability to focus attention to solve novel, complex problems without the use of "previously learned habits, schemas, and scripts" (Schneider & McGrew, 2018, p. 93). It requires both inductive and deductive reasoning (Dehn, 2017; Green et al., 2017; Guerin et al., 2021; see also Schneider & McGrew, 2018). Inductive reasoning is the ability to identify patterns

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[2] The ability to temporarily hold and manipulate information in one's mind to help with a concurrent task (Baddeley, 1986).

within known information and develop a rule to explain the pattern. Deductive reasoning is the ability to use existing rules, concepts, or facts to solve a problem or make a conclusion (Schneider & McGrew, 2018). In a less technical description, G*f* is how one solves unfamiliar problems and shows flexibility in their thinking (Guerin et al., 2021; Otero, 2017; Sofologi et al., 2022). Thus, it is a foundational skill for successfully completing mathematical computations and problem–solving tasks (Green et al., 2017). The link may be that solving mathematical tasks often depends upon relational reasoning which is the ability to understand relationships between the various parts of a problem (i.e., an algebraic equation or word problem[3]; Green et al., 2017). In fact, both G*f* and mathematics involve the fundamental cognitive process of relational reasoning (Miller Singley & Bunge, 2014). The mental manipulation of information—a core component of G*f*—allows one to "reason, plan, and problem solve using attentional, working memory … skills" (Tamm & Juranek, 2012, p. 2).

G*f* is commonly measured through abstract reasoning and visual puzzles that incorporate visuospatial skills such as the matrix reasoning tasks (Blankson & Blair, 2016; Guerin et al., 2021). While exploring the distinctions between visuospatial ability and G*f* in details beyond the scope of this paper, it is important to note that although G*f* and visuospatial skills are strongly correlated, they rely on "separable cognitive processes and brain regions" (Green et al., 2017, p. 127). In G*f* tasks, individuals must identify the relationship between patterns and complete them (McGrew, 2009). Given that G*f* tasks often have low language demands because they may involve pantomime rather than verbal instructions and exclude the use of reading or speaking to solve a problem, it can be considered a measure of NVIQ (Brown, 2003; Otero, 2017). Since

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[3] Mathematical word problems are presented in a linguistic form (i.e., written and/or oral), challenge students to identify important information, and apply mathematical knowledge to develop a solution (Powell et al., 2019; Wang et al., 2016).

autistics are more likely to show challenges in expressive and/or receptive language skills, G*f* seemed the most appropriate construct to assess the relationship between cognitive ability and mathematics among my sample of autistic youth, independent of language. (Note: The relationships between language and various mathematical skills are explored in more detail for autistic and non–autistic youth beginning on page 31). Currently, there are mixed findings on G*f* skills in the autistic population, with some researchers reporting autistics have exceptional G*f* compared to their non–autistic counterparts (Chen et al., 2010; Hayashi et al., 2008; Soulieres et al., 2011), while others not finding this significant difference between the two populations (Devenish et al., 2022; Stevenson & Gernsbacher, 2013). Table 1 lists several key terms related to G*f* and their definitions.

Table 1

Terms Related to Fluid Reasoning

Term	Definition
Fluid Reasoning (G*f*)	The ability to solve complex, novel problems by thinking logically and not relying solely on prior knowledge (Cattell, 1987; Schneider & McGrew, 2018).
Nonverbal Intelligence (NVIQ)	Reasoning to solve a problem without relying on knowledge of language (e.g., reading, speaking, listening, writing; Brown, 2003).
Deductive Reasoning	The ability to use existing rules, concepts, or facts to solve a problem or make a conclusion (Schneider & McGrew, 2018).
Inductive Reasoning	The ability to identify patterns within known information and develop a rule to explain the pattern (Schneider & McGrew, 2018).
Relational Reasoning	The ability to jointly consider the relationships between different components of a problem (Miller Singley & Bunge, 2014).
Perceptual Reasoning	Requires fluid reasoning, visual perception/reasoning, and nonverbal concept formation skills (Cattell, 1963, 1971). For example, the Block Design, Picture Concepts, and Matrix Reasoning subtests of the Wechsler Intelligence Scale for Children -- Fourth Edition are measures of perceptual reasoning (Nader et al., 2014).

Next, I will summarize the literature exploring the relationships between G*f* and mathematical ability (i.e., arithmetic and problem–solving) for children and youth without disabilities, followed by the (albeit limited) literature exploring the relationship among autistic individuals.

The Relationship between Gf and Mathematics in Non–Autistics

Researchers have consistently sought to understand the relationship between broad cognitive abilities (i.e., G*f*) and academic achievement in the non–autistic population. There is moderate to strong empirical evidence for the relationship between G*f* and mathematical achievement (Cormier et al., 2017). McGrew and colleagues (1997) reported that G*f* uniquely predicted mathematical reasoning skills beyond the contribution of overall general intelligence (i.e., *g*; see also Cormier et al., 2017). The following studies found links between various mathematical skills and G*f* among youth without disabilities:

First, using the Woodcock–Johnson III (WJ-III) Tests of Cognitive Abilities and Woodcock–Johnson III Tests of Achievement (Woodcock & Mather, 2001), Floyd and colleagues (2003) looked at the calculation (n = 4,498) and mathematical reasoning skills (n = 3,064) across 14 age groups ranging from 6 to 19 years. They found that G*f* was a significant predictor of arithmetic skills (moderate relations with coefficients ranging from approximately .15 to .20) and mathematical reasoning (moderate to strong relations with coefficients ranging from approximately .15 to .31) across childhood and adolescence. Second, Taub and colleagues (2008) investigated the direct and indirect effects of *g* and G*f* on mathematical achievement across four age groups ranging from 5 to 19 years old. Their outcome variable, quantitative knowledge, comprised of applied problems (i.e., understanding the problem, identifying important information, calculations, and solution statements) and calculations (i.e., simple arithmetic to calculus). They found that G*f* had large, significant direct effects on mathematical achievement across all ages with standardized effects ranging from .37 to .75. They also found that *g* had an indirect effect on mathematics achievement. The authors suggested that G*f* appears to play a role in the strategies students use to solve mathematical problems. Third, in a systematic review, McGrew and Wendling (2010) found G*f* to be a moderate predictor of basic mathematical skills (i.e., math facts and complex algorithmic computations) across all ages (5–19 years) and a strong predictor of mathematical problem–solving ability (i.e., word problems, concepts, and application of operations) for students aged 6–13 years and a moderate predictor for students aged 14–19 years. Fourth, Cormier and colleagues (2017) explored the relationship between several broad cognitive abilities such as G*f*, crystalized intelligence (i.e., general knowledge, verbal comprehension, and vocabulary acquired through formal education; Blankson & Blair, 2016), PSI, and WM and mathematics achievement in children and adolescents (N = 4,194) aged 6–19 years. They found that G*f* had the strongest relation with arithmetic (standardized regression coefficients ranging from .40 to .50) and mathematical problem solving (standardized regression coefficients ranging from .50 to .60) across all ages. Furthermore, they found that all of these broad cognitive abilities accounted for unique variance in arithmetic and problem–solving beyond general intellectual ability. Fifth, in a longitudinal study, Green and colleagues (2017) explored the relative contributions of G*f*, verbal reasoning, and spatial abilities on mathematics performance (i.e., mathematical reasoning, problem solving, and arithmetic ability) of 69 students without disabilities (aged 6–21 years). (There is limited empirical evidence longitudinally exploring the role of G*f*—separate from *g*—on mathematics performance in childhood [Green et al., 2017], and even less so in the autistic population). They found that G*f* was the only significant cognitive predictor of future mathematics achievement 1.5 years later across elementary and secondary grades (Green et al., 2017).

In sum, the research shows a link between G*f* and mathematics achievement in the non-autistic population. It appears that children and adolescents with robust G*f* skills are more likely to have better mathematical performance (Flanagan et al., 2006; McGrew & Wendling, 2010; see also Finn et al., 2014). Given that G*f* is likely an important cognitive skill for mathematics achievement in non–autistics, it is important to understand if this relationship holds true in autistic youth to shed light on how autistic youth develop mathematical skills.

The Relationship between Gf and Mathematics in Autistics

The research on the strength of the associations between G*f* and mathematics in autistic children and adolescents WoID is significantly limited and unclear (Bullen et al., 2020). First, Mayes and Calhoun (2008) explored four broad cognitive domains (i.e., verbal comprehension, perceptual reasoning, WM, and PSI) on language and mathematics achievement in autistic children WoID (n = 54) aged 6–14 years. Of the four broad abilities, they reported that perceptual reasoning was most correlated with numerical operations (r = .77). They also found that FSIQ was the best predictor of overall academic achievement (i.e., reading, writing, mathematics). In a more recent study, Oswald and colleagues (2016) explored the cognitive characteristics associated with mathematical problem–solving (i.e., untimed problems using basic skills, everyday applications such as knowledge of money, geometry, and algebra) in 27 high–achieving autistic adolescents and 27 non–autistic peers. They reported that perceptual reasoning was significantly correlated (r = .54) with mathematical problem–solving. They also found that perceptual reasoning was the strongest predictor of mathematical problem–solving skills above and beyond verbal ability, test anxiety, and autism diagnosis, accounting for 21.6%

of the variance in the model. A study exploring the relations between attention and G*f* on academic achievement in school–age autistic children (*N* = 32) found that G*f* was most significantly, positively correlated (*r* = .69) with mathematics achievement. They also found that both attention and G*f* predicted overall academic achievement (i.e., reading, writing, and mathematics; Spaniol et al., 2021). In contrast, Assouline and colleagues (2012) did not find a significant correlation (*r* = .33) between perceptual reasoning and mathematical performance in their sample of autistic youth WoID (*N* = 59; aged 5–17 years). Furthermore, Troyb and colleagues (2014) examined the academic abilities of 32 students who were previously diagnosed with autism, 41 autistics WoID, and 34 non–autistic peers (aged 8-21 years; matched on age, sex, and NVIQ), reporting that the autistic participants WoID performed significantly lower on mathematical problem–solving tasks than the previously diagnosed participants, even when matched on NVIQ. Findings from the two aforementioned studies could suggest that other individual characteristics may be involved in the differences in mathematics achievement of autistic youth.

In sum, numerous studies have consistently indicated that G*f* appears to be an important cognitive factor in determining mathematics achievement among the non–autistic population. However, the available literature on autistic children and youth lacks the same level of robustness and clarity. While some researchers have reported that G*f* plays a role in the mathematical performance of autistic youth, others have disputed this finding. Therefore, my study explored the influence of G*f* on the mathematical ability (i.e., computations and applied problems) of autistic youth as future research on this topic is necessary. Moreover, since some researchers have found no significant relationships between these variables, it is imperative to explore alternative predictors that may account mathematical ability. Such knowledge could offer valuable insight into how autistic individuals learn mathematical concepts.

Language

Linguistics—the "study of language systems" (Brinton, 2000, p. 10)—is divided into five modules when understanding English: Phonology, morphology, syntax, semantics, and pragmatics. Although they are interrelated components, they can be defined separately, each having a specific role in the acquisition of language skills (Brinton, 2000). Brinton's (2000) book on the structure of modern English defines each module: Phonology is understanding the sounds of language (e.g., vowels, consonants) that is spoken and heard. Morphology is the structure of words—understanding how sounds are put together to make a meaningful word as well as how words are made of different parts and put together (e.g., prefixes, suffixes, and roots). Syntax or grammar is the study of how words are arranged based on rules to create different types of sentences (e.g., questions), phrases, and clauses. Semantics refers to how individuals make meaning of words and sentences. Last, pragmatics refers to how language is used for communicating with others which is dependent on the social setting in which one is interacting (e.g., formal speech versus conservational speech, expressing emotion, connecting with close ones). Phonological awareness (related to phonology), orthographic knowledge (spelling words by understanding the units within the words; Zaric et al., 2021), and morphological awareness (related to morphology) are important skills for word decoding. While semantic, syntax, vocabulary, and inferences are important skills for language comprehension (e.g., listening comprehension; Conners, 2009; Gough & Tunmer, 1986; Hoover & Gough, 1990). In the following section, I provide a brief overview of the language abilities of autistics WoID.

Language Abilities of Autistics WoID

The structural language abilities of autistic individuals, such as their understanding of meaning (i.e., semantics) and grammar (i.e., syntax), display a lot of individual variability (Friedman & Sterling, 2019). Some researchers have shown that on average, autistic individuals have weaknesses in language (e.g., semantics) in comparison to their non–autistic peers (Ambridge et al., 2015; McIntyre et al., 2017; Park et al., 2012; Troyb et al., 2014), while others have found relatively intact word reading and syntactic abilities (e.g., Jones et al., 2009; Kim et al., 2017; Modyanova et al., 2017). The following studies describe the language abilities of autistic children and adolescents:

In a meta–analysis of 74 studies exploring expressive (i.e., to produce spoken language) and receptive language skills (i.e., to comprehend spoken language), Kwok and colleagues (2015) found that autistic children and youth experienced relatively equal challenges with both expressive and receptive language skills (generally one and a half standard deviations below their non–autistic peers), and reported that the differences between receptive and expressive language were not clinically meaningful (see also Girolamo et al., 2022). McIntyre and colleagues (2017) identified reading profiles in autistic students WoID (*n* = 81; aged 8–16 years) by examining their phonological processing (i.e., letter–sound recognition; Flanagan & Alfonso, 2011), basic real–word and nonsense word reading, language comprehension (i.e., receptive and expressive language), and reading comprehension (i.e., reading passages). The researchers found that 20% of their sample had reading comprehension difficulties, 33% had a ‘global disturbance’ (i.e., scoring one standard deviation below the national average on all reading measures), and 14% were identified as having ‘severe global disturbance’ in reading (i.e., two standard deviations below average on inferences, expressive language skills, narrative retelling, and comprehension). Rather than looking at group means between autistics and non–autistics, Wei and colleagues (2015) explored the reading achievement (i.e., letter word identification, rapid letter naming, and passage comprehension) of 130 autistic children (aged 6–9 years) at an individual level by grouping them into four achievement profiles. They found that 38.5% of children had average (within one standard deviation from the mean) reading skills across all measures, 9.2% had average letter word recognition and passage comprehension but above average rapid letter naming, 20% had below average (one standard deviation) reading across all three measures, and 32.3% scored below the national average (two standard deviations) across all three measures.

The previous research provides evidence suggesting that autistic children and adolescents tend to have below average language abilities compared to their non–autistic peers. However, as illustrated by Wei and colleagues (2015), autistic children may also present with average language abilities. I decided to investigate if the language difficulties that autistic youth encounter may be a contributing factor to their mathematics achievement.

How is Language Related to Mathematical Skills Among Non–Autistics?

Since language plays a vital role in overall learning, it may influence the development of mathematical skills (De Smedt et al., 2010) and predict mathematics achievement (Purpura et al., 2011; Zhang et al., 2017). Language skills support mathematical performance of non–autistic children and youth in varied ways which is discussed in the following studies:

Vocabulary is important because mastery of mathematical terms may play a role in mathematics achievement. Mathematical vocabulary are words used to communicate concepts (i.e., volume, diameter, equation; Brown et al., 1994). In fact, mathematical word problems are unique from other types of reading comprehension tasks due to the inclusion of mathematical vocabulary (Fuchs et al., 2015). Bae and colleagues (2015) found that mathematical vocabulary was significantly positively associated ($r = .69$) with word problem solving (e.g., story problems). In a meta–analysis with 98 empirical studies, Lin (2021) found that mathematical vocabulary was a significant predictor of word problem–solving in older students (grades 3–5; $\beta = .21, p < .05$), but not for younger students (kindergarten to grade 2). This could be because mathematical vocabulary becomes increasingly complex as students enter higher grades (Powell et al., 2017). Thus, it appears that mathematical vocabulary is an important skill to solve word problems in non–autistic and autistic children.

However, an understanding solely of mathematical vocabulary may render a student unable to fully comprehend a mathematical word problem. Due to the conceptually demanding structure of mathematical word problems that involve many cognitive (e.g., verbal comprehension, WM, G*f*) and academic (e.g., language comprehension, mathematical vocabulary, math facts retrieval) skills (Lin, 2021), students may struggle since these problems typically also require language comprehension skills. **Language comprehension** (i.e., defining vocabulary and listening comprehension skills; Lin, 2021) is a necessary skill in learning mathematics because students are likely going to deepen their understanding of mathematical concepts by reflecting, clarifying ideas with others, and communicating solutions to problems (Ontario Ministry of Education, 2005). In fact, **verbal comprehension** (i.e., verbal intelligence [VIQ] is the ability to comprehend and verbalize concepts and reason using language; Wechsler, 2014) and language comprehension may be important skills for solving mathematical word problems (Fuchs et al., 2015; Peng & Lin, 2019). In their sample of 88 non–autistic children (aged 6–12 years), Rowe and colleagues (2010) found that verbal comprehension was significantly positively correlated ($r = .36$) with overall mathematical ability (measured with the

WIAT-II (I.e., numerical operations and mathematical problem solving) and a significant predictor, accounting for 8% of the variance.

Lin (2021) reported that language comprehension was a significant predictor for word problem–solving among older students (grades 3–5; $\beta = .19$, $p < .05$), while nonverbal reasoning, WM, and attention were other contributing variables to the model. Moreover, reading comprehension was not a unique academic predictor of word problem solving, likely due to the oral format of the word problems. Furthermore, Spencer and colleagues (2020) assessed students' mathematics (i.e., arithmetic and mathematics fluency), oral language (i.e., vocabulary, listening comprehension, and word identification fluency), and G*f* abilities in grade 2 and then assessed them on mathematics word problem–solving in grade 4. They found that prior oral language accounted for unique variance in grade 4 word problem solving beyond the contributions of prior word problem solving, computation, and G*f* abilities ($\beta = 0.351$, $p < .001$). In a study exploring the language skills (i.e., vocabulary and listening comprehension) of 167 non–autistic children (aged 6–9 years) on mathematics development, Vukovic and Lesaux (2013) found that grade 1 language ability predicted gains in grade 4 data analysis/probability ($\beta = .67$, $p < .05$). Furthermore, grade 2 language ability predicted gains in grade 4 geometry domains ($\beta = .32$, $p < .05$) while controlling for visual–spatial WM, reading ability, and sex. The researchers did not find this result with arithmetic and algebra, suggesting that general language ability may be important for conceptual understanding of mathematics that does not rely on "manipulating exact numbers through procedures and algorithms" (p. 240).

There is evidence to suggest that language ability influences mathematics achievement in non–autistic children and youth, specifically through mathematical vocabulary, verbal comprehension, and language comprehension. This relationship has been more commonly explained through the impact of language on mathematical word problem solving skills. The next section will describe how language plays a role in autistic youths' mathematics achievement.

How is Language Related to the Mathematical Skills of Autistics?

Based on the brief overview of the connection between language and mathematics in non–autistic students, it becomes clear that different aspects of language impact mathematical achievement. As language encompasses a broad range of abilities (e.g., verbal comprehension, vocabulary, reading comprehension, inferences), its various domains can influence mathematical achievement differently depending on factors such as the age of the student and other relevant variables like WM. It is evident that links between language and mathematics exists in non-autistics. Yet, given the scant research with autistics, it is unclear how autistic youths' language abilities impact their mathematics achievement. This underscores the importance of further exploring this connection in the autistic population. The following studies describe the research published to date exploring the relationship between mathematics skills and language among autistic youth:

There are mixed findings on the influence of sentence comprehension, word reading, and vocabulary on mathematics ability in autistic youth. First, Chen and colleagues (2019) found that in a sample of 114 autistic males (aged 7–12 years), word reading and reading comprehension were significantly and positively correlated with numerical operations (r = .46 and .35, respectively) and mathematical reasoning (r = .61 and .62, respectively). Furthermore, across low– and high–ability autism groups for numerical operations, they found that students in the high–ability group had significantly better word reading (d = 1.45) and reading comprehension scores (d = 1.46). Interestingly, the researchers reported that approximately 40% of their autistic sample had mathematics challenges that were not associated with reading difficulties. Second, Miller and colleagues (2017) reported that their autistic participants (*N*= 26; aged 8–10 years) had lower scores on mathematical reasoning (i.e., requiring problem–solving ability) and reading comprehension compared to numerical operations and single word reading tasks. However, these differences were not statistically significant, unlike other studies (see Bae et al. 2015; Troyb et al., 2014). They proposed that since mathematical reasoning tasks often have a linguistic demand, it is likely that difficulties with mathematical reasoning are due to challenges with language comprehension. Third, in a study comparing the mathematical word problem–solving ability (using two measures) of 20 autistic and 20 non–autistic children (M_{age} = 10 years), Bae and colleagues (2015) found that sentence comprehension ($r = .69$ and .62), mathematical vocabulary ($r = .69$), and everyday mathematical knowledge ($r = .76$ and .71) were significantly positively correlated with autistic (and non–autistic) children's word problem–solving skills, however, word decoding was not. They also reported that the non-autistic children had significantly higher word problem–solving skills than the autistic children ($d = .92$–1.15) due to significantly higher mathematical knowledge ($d = .90$). However, when controlling for mathematical knowledge, there were no differences in mathematical word problem solving ability between the groups. Bae and colleagues' (2015) study illustrates that when considering a student's mathematical knowledge in the model, it becomes important for their mathematics achievement beyond language skills (i.e., sentence comprehension). Fourth, Bullen and colleagues (2020) reported reading comprehension was not a significant predictor of mathematical problem solving (using the WIAT-III) in their regression analyses at time point one ($\beta = .21$, $p > .05$) and time point three ($\beta = -.01$, $p > .05$). Although some researchers have found significant correlations between these language domains and mathematics achievement, further research is needed in this area.

Additionally, several researchers have highlighted the importance of verbal comprehension in the acquisition of mathematical abilities. For example, Polo-Blanco and colleagues (2022) explored the relationships between mathematical problem–solving (i.e., arithmetic word problems) and cognitive predictors (e.g., EF and verbal comprehension) in 26 autistic and 26 non–autistic children. They found a higher percentage of autistic children struggled with arithmetic word problem–solving compared to the non-autistic group (57% versus 23%). Furthermore, they found that autistic children who had poorer mathematics achievement (i.e., answered less than 25% of responses correctly) also had significantly lower verbal comprehension scores ($\eta^2 = .19$) than the other autistics, as measured by the Weschler Intelligence Scale for Children–5 (WISC-V; Wechsler, 2014); this relationship was not seen in the non-autistic group. In a study with 27 autistic adolescents, the researchers found that verbal comprehension was the second strongest predictor of mathematics problem–solving skills, after accounting for NVIQ ($\beta= 0.30$, $p < .05$; Oswald et al., 2016). In contrast, Assouline and colleagues (2012) reported that verbal comprehension was not significantly correlated ($r = .05$, $p > .05$) with mathematics achievement in their sample of gifted autistic students.

There is a larger body of evidence showing that language influences mathematics achievement in non–autistic individuals. However, the evidence is variable with regards to the autistic population where some studies depict a relationship between language (mostly verbal comprehension) and mathematical ability, while others suggest otherwise. In light of the limited research, my study explored the impact of expressive language on mathematical ability by determining if language is a predictor of mathematics achievement of autistic youth. Considering the co–occurrence of mathematical and reading difficulties in autistic children WoID (Bullen et al. 2022), it is conceivable that language abilities might have an impact on mathematics achievement.

Having said this, the varying findings on the impact of language on the mathematical performance of autistic individuals raise the possibility that there may be additional factors influencing students' outcomes in mathematics. Titeca and colleagues (2015) explored autistic children’s (aged 6–10 years) word/language problem solving skills. The authors suggested there are different kinds of mathematical word problems—ones that are straightforward and clear, compared to complex paragraphs with irrelevant details that require WM efforts to hold multiple pieces of information in one’s mind. The researchers found that autistic children's performance in grades 2 and 4 fell in the above average range for word/language problems that were short and succinct (i.e., one–sentence problems that can be solved using only the keywords). The also found children fell in the above average range in grade 4 for word/language problems that had more contextual information (i.e., multiple sentences). This finding is consistent with Iuculano and colleagues (2014) who also found intact word problem solving abilities. Perhaps this study gives researchers one of the first clear signs that traits beyond language ability may play an important role in the development of strong mathematical skills among autistic youth, namely executive functions.

Executive Functions

EF refers to a set of overlapping cognitive skills used to regulate attention and goal-directed behaviour (Diamond, 2013). It is essential in language (Sesma et al., 2009) and mathematics (Gerst et al., 2017; Ribner et al., 2017) development and develops during childhood (Pascual et al., 2019). EF is an overarching concept comprising several cognitive functions, such as WM (i.e., mentally holding and manipulating information temporarily), cognitive flexibility

(CF; i.e., to switch between ways of thinking or tasks to develop solutions), planning and organizing as well as emotional and behavioural regulation (Anderson, 2002; Baddeley, 1996; Braem & Egner, 2018; Friedman & Sterling, 2019; Matthews et al., 2005; Sesma et al., 2009).

EF Skills in Autistics WoID

Several researchers have found that autistics often have decreased EF skills at the group level compared to non–autistic peers (Craig et al., 2016; Eylen et al., 2015). However, like language, there is greater variability when looking at individual differences (Friedman & Sterling, 2019) and some autistics have intact EF (Pellicano, 2010). Furthermore, mixed findings may be due to the nature of tasks autistic individuals are asked to complete (Van Eylen et al., 2015). Additionally, given the vast number of EF skills and autism heterogeneity, it may be difficult to find converging evidence (Blijd–Hoogewys et al., 2014; Craig et al., 2016; Geurts et al., 2014). The following section describes the research on autistics' EF skills:

In a review on autism and EF, Friedman and Sterling (2019) found that studies have reported mixed findings on autistics' EF abilities in the subdomains of CF, inhibition, and WM. Some researchers have reported that autistics have challenges with CF compared to those with developmental language disorder, attention–deficit/hyperactivity disorder (ADHD), and non-autistic peers, meanwhile, others have not found CF weaknesses in the autistic population (see Leung et al., 2014). Like CF, Friedman and Sterling (2019) described how existing research has mixed findings on the inhibition and WM abilities of autistic children and adolescents with some researchers reporting no differences between autistic and non–autistics and others finding weaknesses (see also Golshan et al., 2019; O'Hearn et al., 2008). In contrast, the authors of the review described how there is generally a consensus in existing research that autistic individuals tend to have difficulties with planning compared to other populations (i.e., non–autistics, ADHD, and Tourette's syndrome).

Demetriou and colleagues (2018) conducted a meta–analysis comparing the overall EF (i.e., encompassing all EF subdomains) and individual EF subdomains of autistics (*N* = 6816) to non–autistics (*N* = 7265) in 235 studies (aged 6–18+ years). They reported a statistically significant and moderate effect size (Hedges' *g* = .68) for reduced overall EF in autistics, suggesting that on average, autistics have EF weaknesses compared to their non-autistic peers. At the EF subdomain level (i.e., mental flexibility, fluency, planning, inhibition, and WM), they found moderate effect sizes across all subdomains (Hedges' *g* = .45–.55) in autistics, and that the subdomains were not significantly differentially impaired. When looking at only children, effect sizes were moderate across all subdomains (Hedges *g* = .48–.62). Similarly, a different meta-analysis (Lai et al., 2017) explored EF subdomains by comparing autistic children and adolescents WoID (*N* = 2,986; M_{age}= 10.65) to non–autistics (*N* = 3,005; M_{age}= 10.81) peers across 98 studies. Even when controlling for IQ and co–occurring ADHD diagnosis, the autistic participants showed greater difficulties with CF (Hedges *g* = .57–.61), generativity (i.e., the ability to create spontaneous and novel answers; Hedges' *g* = .52–.68), and WM (Hedges' *g* = .49–.56). In another study not included in the previously mentioned review and meta–analyses, the authors re–analyzed the data of three different studies with autistic (*n* = 93), ADHD (*n* = 104), and non–autistic children (*n* = 93; aged 6–18 years) to compare the heterogeneity in EF skills (i.e., planning, flexibility, WM, and inhibition). They found that in fact, approximately 10–34% of the autistic children had significant difficulties across these EF subdomains (Geurts et al., 2014).

Although some researchers have found comparable EF skills between autistic and non-autistic individuals, the consensus within the scientific community is that autistics generally have EF difficulties. Given this it is possible that EF weaknesses could impact an individual's mathematics achievement. The next section seeks to provide clarity on the relationship between EF and mathematical ability.

How is EF Related to the Mathematical Ability of Non–Autistics?

Researchers have established EF as an important predictor of mathematical performance in non–autistic individuals (Bull et al., 2008; Gerst et al., 2017; Pascual et al., 2019; Stevenson et al., 2014). EF assists with completing many mathematical–related tasks. For example, it helps us to decide which strategies to use to answer questions (goal–directed behaviour), switch between operations (CF), recall steps to solve complex problems (WM), and remember a sequence of numbers while ignoring irrelevant information (inhibition; Assel et al., 2003; Blair et al., 2015; Bull & Lee, 2014; Menon, 2010). Although EF skills are interconnected, researchers have often found that certain EF skills support specific mathematical abilities (Alloway & Passolunghi, 2011; Bull & Scerif, 2001; LeFevre et al., 2013; St Clair–Thompson & Gathercole, 2006). For example, some researchers have found that auditory WM is necessary for calculations, whereas CF and planning aid in solving complex mathematical problems (Kim & Cameron, 2016; Gerst et al., 2017; Purpura et al., 2017; Raghubar et al., 2010). Due to the scope of this paper, the following section will describe research on the links between WM and CF and mathematics achievement in non–autistics:

Regarding academic achievement research, WM stands out as one of the key EF skills that has garnered significant attention (Pascual et al., 2019). Researchers of a review and meta–analysis ($k = 21$, $n = 7{,}947$) on the relationship between EF and academic achievement in non–

autistic students (aged 6–12 years) found a moderate correlation between WM and academic achievement ($r = .37$) compared to other EF subdomains (e.g., inhibition, CF, planning). They also found moderate correlations between mathematics (reasoning, calculus, and arithmetic) and relation to overall EF ($r = .36$) and WM ($r = .37$), which were better correlated than with language ($r = .35$, $r = .33$; Pascual et al., 2019). To further illustrate this point, Tsubomi and Watanabe (2017) explored the relationship between visual WM and academic performance in non–autistic children ($N = 140$; aged 7–12 years) by asking children to remember a visual image accompanied by one of three conditions—blank (visual WM storage), visual distractor, or verbal distractor. Regarding mathematics, visual WM supports multi–digit calculations (Trbovich & LeFevre, 2003) and extracting numbers from graphs, charts, and tables (Holmes et al., 2008). They found that visual WM storage (without distraction) uniquely predicted children's mathematical scores ($\beta = .27$, $p < .05$) for the younger group (aged 7–9 years), and visual WM with distractor resistance uniquely predicted mathematical scores ($\beta = .39$, $p < .01$) for the older group (aged 10–12 years). The authors hypothesized that younger children learn simpler mathematical concepts which could explain the role of visual WM storage, whereas older children learn more complex content and need to be selective with the information they store in visual WM, thus giving more importance to distractor resistance. Researchers have consistently demonstrated that strong WM skills are a unique predictor of mathematics achievement (e.g., word problem solving; Fuchs et al., 2016) in non–autistic children, even after accounting for the influence of G*f*, reading, and arithmetic abilities (Swanson, 2011; Swanson et al., 2008).

CF requires individuals to engage in task switching (e.g., switching between two instructions) and set shifting (e.g., shifting attention between different aspects of the stimuli; Dajani & Uddin, 2017), and has been found to predict the mathematical achievement of non-autistic children aged 4 through 13 years (Yeniad et al., 2013). Although researchers suggest that CF enables students to transition between different types of procedures or numerical operations in mathematical questions, there is less extensive research available on the association between CF and mathematics (St. John et al., 2018). Gerst and colleagues (2017) found that inhibition ($\beta = -.27$, $p < .001$) and planning ($\beta = .16$, $p < .05$) were predictors of calculation ability, beyond other EF skills (i.e., WM). Clark and colleagues (2010) reported that participants' ($n = 104$) grade 1 mathematics fluency was predicted by their overall EF (measured with the BRIEF-Preschool; $\beta = -.24$, $p < 0.05$), along with IQ and passage comprehension in preschool. In a large study of 1292 participants, the researchers investigated the role of EF at five years old in predicting grade 5 mathematical ability beyond early mathematical ability (i.e., applied problem solving such as counting and operations; Ribner et al., 2017). The results were twofold: First, they found that early mathematics ($\beta = .367$, $p < 0.001$) and EF ($\beta = .209$, $p < 0.001$) significantly and uniquely predicted later mathematical ability. Second, the relationship between a child's grade 5 mathematical ability and early mathematical ability changed depending on their early EF skills (i.e., the variance explained by early mathematical ability on grade 5 mathematics ability was reduced if the child had high EF skills).

The research has demonstrated that EF skills impact mathematical ability. EF is a broad area encompassing many subdomains and researchers have identified consistent relations between EF subdomains and mathematics achievement. WM supports tasks that involve calculations, whereas CF supports more complex mathematical problems. Given that there is strong evidence to suggest that EF skills are important for mathematical achievement, and that EF may be reduced within autistic populations, the next section will explore the relationship between EF and the mathematical ability of autistics.

How is EF Related to the Mathematical Ability of Autistics?

Despite the plentiful data on the role of EF in non–autistic students' mathematics achievement, there is limited research on the autistic population (St. John et al., 2018). EF plays a role in understanding mathematics (Ribner et al., 2017), thus may be a concern for autistic individuals who may have difficulties with EF skills (Craig et al., 2016; Dajani & Uddin, 2015; Habib et al., 2019; Semrud–Clikeman et al., 2014; Wang et al., 2017). Compared to non–autistic children of the same age and academic level, children with a specific learning disability (SLD) in mathematics demonstrate limited verbal and visual–spatial WM abilities (Swanson & Jerman, 2006). In fact, Kercood and colleagues (2014) who conducted a literature review on autism and WM found that autistic children had similar WM profiles to children with a SLD in mathematics. The following studies describe the links between EF and mathematics achievement in autistics.

One study exploring mathematics achievement (i.e., verbal problem solving and numerical operations using the WIAT-III; Wechsler, 2009) in school–age autistic children found significant correlations between three types of WM (i.e., story memory, verbal, and symbolic) and problem solving ($r = .40–.62$) and numerical operations ($r = .23–.55$). These associations were not statistically significant across all three types of WM in the non–autistic group. Furthermore, at time point one, only symbolic WM was a significant predictor of numerical operations accounting for 8% of the variance compared with verbal IQ, visuospatial ability, and reading comprehension and fluency. Secondly, symbolic and verbal WM ability accounted for 6% of the variance in problem solving (Bullen et al., 2020). Similarly, Chen and colleagues (2019) reported that WM scores were significantly positively correlated with numerical operations ($r = .50–.51$) and mathematical reasoning ($r = .49–.53$) subtest scores in their autistic sample ($n = 114$). They also found that verbal WM ($z = 2.50$, $p < .05$) and the central executive of WM ($z = 2.21, p < .05$) significantly predicted group membership (i.e., low or high academic achievement ability) in the autistic group; higher WM scores were significantly associated with the high–ability autism subgroup ($d = .66–1.08, p < .01$). Further support for EF in mathematics achievement was shown by Bullen and colleagues (2022) who described two mathematics achievement groups—low ability (less than one standard deviation below the norm–referenced mean) and high ability (greater than one standard deviation above the norm–referenced mean). They found that the high ability group had higher performance on all WM tasks than the low ability group with large effect sizes ($d = -0.73$ to -1.12). Lastly, EF also has been shown by St. John and colleagues (2018) to be a future predictor of mathematical achievement. They investigated the relationship between EF (i.e., WM, inhibition, and set shifting [i.e., CF]) and academic achievement in 32 autistic children (9 years old). They found high EF skills at age 6 was predictive of increased mathematical performance at age 9, accounting for 9% of the variance beyond the contributions of IQ.

In contrast to these findings, Oswald and colleagues (2016) reported WM was not significantly correlated ($r = .36, p > .05$) with applied mathematical problem–solving (e.g., everyday applications [e.g., time], algebra, and geometry) of autistic students. Further regression analyses found that WM was also not a significant predictor while including autism diagnosis, verbal IQ, NVIQ, and test anxiety in the model. The researchers proposed their mathematical problem–solving tasks potentially placed fewer demands placed on WM compared to other studies (e.g., providing participants with an additional paper to work out the problems). Overall, researchers have reported a link between EF and mathematics achievement in autistic children and youth, which is consistent with the findings in the non–autistic population. Additionally, based on the results from Oswald and colleagues (2016), autistic students who have weaker EF skills may benefit from receiving support in this domain which will in turn impact their mathematical performance.

Current Study

Autistics' strengths in mathematics have been commonly presented in popular culture. This idea can be harmful to autistic individuals as it puts undue pressure on them to succeed. Contrary to this notion, researchers have found a large proportion of autistic students with average and below-average mathematical abilities. My study sought to further understand this variability which may also help to alleviate existing stereotypes. Since I expected variability in my sample of autistic youth, I also explored the individual characteristics that may explain this variability. The relationship between G*f* and mathematics achievement within non–autistic populations has been extensively explained. Whereas the evidence for the relationship between G*f* and mathematics achievement in autistic children and youth is inconclusive. Given that G*f* is highly correlated with *g* (Reynolds et al., 2013), this study sought to further explore its role in the mathematical achievement of autistic youth. Researchers have suggested that solving mathematical problems requires an individual to recall important information whilst being able to switch attention and hold several concepts in their mind—exhibiting the coordinated use of several EF skills (Geary, 2013). Autistic students may face challenges when solving complex, multi–step mathematics problems. They may find it difficult to filter out irrelevant information while retaining the important details. Additionally, challenges with language may further hinder their mathematics achievement. These difficulties may arise because they need to rely on both conceptual understanding and procedural knowledge to arrive at a solution (Root et al., 2018; Titeca et al., 2015). To this end, my study focused on how G*f*, expressive language, and EF impact autistic youths' mathematics achievement.

The purpose of this research is twofold:

A. **To explore and describe the heterogeneous and dynamic mathematical ability profiles of autistic youth (aged 5 through 16 years)**
   i. by identifying the relative proportions of autistic youth who scored above and below average in mathematical ability; ± 1 *SD* of the norm).

B. **To identify predictors of mathematical ability among autistic youth**
   i. by exploring the relative contributions of *Gf*, expressive language, and EF to overall mathematical ability (e.g., counting, estimation, arithmetic, geometry, and problem solving).

Method

Participants

Graduate students and research assistants in Dr. Heather Brown's research lab at the University of Alberta collected the original data from 81 potentially eligible participants. With Dr. Heather Brown's strong and long–standing community connections, convenience sampling was conducted by posting notices on local Facebook pages and websites of autism agencies, in monthly newsletters, and at local events (e.g., the annual Cycle for Autism) and presentations. Participants were excluded from my analyses if a) they were missing data (*n* = 35), b) had a G*f* score less than 70 due to a potential intellectual disability (*n* = 3), c) had an expressive language score less than 4 due to a potential language–based learning disability (*n* = 4), and/or d) did not have an autism diagnosis (*n* = 6). We chose to keep autistic youth with very high G*f* and/or expressive language skills in the sample as we hoped to capture the full range of mathematical ability among autistic youth who did not also have co–occurring intellectual or language–based learning disabilities. The participants' parents reported their child's autism diagnosis and the source of the diagnosis (i.e., multidisciplinary team, neuropsychologist, pediatrician, psychologist, or psychiatrist); however, our study did not independently confirm this (Table 2). Given my interest in the heterogeneity of mathematics achievement and the study's research questions, there were no inclusion or exclusion criteria for mathematical ability. Based on this inclusion criteria, 33 autistic boys (assigned male at birth - AMAB; *n* = 31) and girls (assigned female at birth—AFAB; *n* = 2) aged 5–16 years (*M* = 9.85, *SD* = 3.49) participated in this study. Each participant completed several assessments to measure mathematical ability, G*f*, and expressive language, and their parent/guardian completed two questionnaires to capture a sense of each youth's EF skills and autistic characteristics.

Table 2

Participant Demographics

Characteristic	*n*	% of total sample size
Gender		
Male	31	93.94
Female	2	6.06
Diagnosis[a]		
Autism	27	81.82
Asperger's	5	15.15
Source of diagnosis[b]		
Multidisciplinary team or clinic	17	51.52
Neuropsychologist	1	3.03
Pediatrician	6	18.18
Psychiatrist	4	12.12
Psychologist	2	6.06
Unspecified medical clinician	2	6.06
Co–occurring conditions[c]		
None	17	51.52
+ Attention–deficit hyperactivity disorder (ADHD)	7	21.21
+ Anxiety disorder	1	3.03
+ >1 co–occurring condition[d]	6	18.18

Note. All information is self–reported according to participants' parent(s)/caregiver(s). Where possible, specific verbiage was retained to create the categories reported in this table (i.e., care was taken to respect use of either "Autism" or "Asperger's").

[a] missing responses *n* = 1

[b] missing responses *n* = 1

[c] missing responses *n* = 2

[d] Among the 6 participants with more than 1 co–occurring condition, they listed the following: ADHD (*n* = 4), anxiety (*n* = 3), obsessive compulsive disorder (*n* = 2), Tourette's (*n* = 1), challenges in communication (*n* = 2), challenges in reading and/or writing (*n* = 2), challenges in mathematics (*n* = 1).

Measures

Mathematical Ability

Mathematical ability was measured using the *KeyMath-3 Diagnostic Assessment: Canadian Edition* (KeyMath-3 DA^{CDN}; Connolly, 2008). This measure is a norm–referenced, standardized test for students 5 years to 17 years, 11 months. KeyMath-3 DA ^{CDN} is a comprehensive assessment that measures mathematical skills using ten subtests across three core content areas: Basic Concepts (conceptual knowledge), Operations (computational skills), and Applications (problem solving). KeyMath-3 DA^{CDN} has two parallel forms, Forms A and B (M = 100, SD = 15); for this study, the participants verbally completed Form A, which contains 372 full–colour visual test items. KeyMath-3 DA ^{CDN} takes approximately 30–90 minutes to administer using paper and pencil. Due to the COVID-19 pandemic, data collection was interrupted. We included the subtests, composite scores, and participants with the most information available (i.e., KeyMath-3 DA ^{CDN} Basic Concepts and Applications).

The KeyMath-3 DA ^{CDN} Basic Concepts composite includes five subtests: Numeration, Algebra, Geometry, Measurement, and Data analysis/probability (see more details below). Each KeyMath-3 DA^{CDN} Basic Concepts subtest requires students to demonstrate both procedural and computation mathematics skills:

- The **Numeration** subtest measures an individual's foundational understanding of mathematical concepts including knowledge of whole numbers and rational numbers such as fractions, rounding, decimal values, percentages, exponents, and square roots.
- The **Algebra** subtest measures algebraic understanding such as sorting, patterning, variables, equations, and mathematical relationships.

- The **Geometry** subtest measures one's ability to analyze, describe, and compare two-dimensional and three–dimensional shapes such as spatial reasoning, symmetry, and angles.
- The **Measurement** subtest measures knowledge and estimation of angles, time, counting (i.e., money), and the ability to select appropriate measurement units.
- The **Data Analysis/Probability** subtest measures knowledge of probability and the ability to collect, display, and interpret data using charts, graphics, and tables.

In comparison, the KeyMath-3 DA $^{\text{CDN}}$ Applications composite includes two subtests: Foundations of Problem Solving (i.e., word problems, problem–solving strategies) and Applied Problem Solving (i.e., across the five domains). The Applications composite requires students to demonstrate operational skills to solve the mathematical problems:

- The **Foundations of Problem Solving** subtest assesses how well the student can identify important elements to solve a mathematical problem (e.g., operations required and strategies).
- The **Applied Problem Solving** subtest assesses the student's ability to use their conceptual knowledge (across the five domains) and calculation skills to find a solution to the problem.

KeyMath-3 DA$^{\text{CDN}}$ uses start points and basal and ceiling rules to allow for an accurate estimation of mathematical ability (Hieftje et al., 2017). Given that Basic Concepts is strongly correlated with KeyMath-3 DA$^{\text{CDN}}$ total test score (r = .96) and the Applications composite (r = .97), it was chosen as the composite for the regression analysis (described below). Split–half reliability coefficients for KeyMath-3 DA$^{\text{CDN}}$ Basic Concepts Form A for students aged 5 to 17 years ranges from .83 to .97 and from .72 to .92 for Applications (Connolly, 2008). Test-retest reliability coefficients from kindergarten to grade 12 range from 0.91–0.95 for Basic Concepts and 0.85–0.91 for Applications (Connolly, 2008). The KeyMath-3 DA^{CDN} manual explains that experts and consultants were part of the content validity process. Furthermore, the manual provides comprehensive data on the assessment's construct validity with tables showing the correlations between KeyMath-3 DA^{CDN} and other measures that test similar content.

Fluid Reasoning

G*f* was measured using the *Raven's Coloured Progressive Matrices* (Raven's CPM; Rust & Raven, 2008a) or the *Raven's Standard Progressive Matrices–Plus version* (Raven's SPM+; Rust & Raven, 2008b). Both age–normed versions have a mean composite score of 100 and a standard deviation of 15. Raven's CPM is a coloured, untimed, 36–item standardized measure for students aged 4 to 11 years and takes approximately 30 minutes to administer (Rust & Raven, 2008a). Raven's SPM+ is a black–and–white, untimed, 60–item standardized measure for students aged 7–18 years and takes approximately 60–90 minutes to administer (Rust & Raven, 2008b). Researchers used the publisher's guidelines and clinical judgement (including the participant's age, level of engagement, attention span) to determine which version of the measure the participant received (for those children between the ages of 7 and 11 years). To complete the Raven's CPM or Raven's SPM+, participants had to examine visual geometric designs arranged in a matrix and determine the missing piece in the pattern from several options. The language requirements for the Raven's test are minimal; students must understand scripted verbal instructions, supplemented with pointing gestures for better task comprehension. The manual for the Raven's CPM (Rust & Raven, 2008a) reported a split–half reliability coefficient of .97 and the Raven's SPM+ (Rust & Raven, 2008b) manual reported a split–half reliability coefficient of .94. The validity of each version of the Raven's Progressive Matrices is based on strong correlations with previous versions of the measure and factor analysis studies (Rust & Raven, 2008a, 2008b).

If the participant did not have a Raven's SPM+ or Raven's CPM score (*n* = 6), then G*f* was measured with the *Leiter International Performance Scale, Third Edition* (Leiter-3; Roid et al., 2013). The Leiter-3 is a norm–referenced, standardized measure of NVIQ and visualization skills. This measure is for individuals aged 3–75+ years and takes approximately 45 minutes to administer (Roid et al., 2013). The subtests have pantomime and non–vocal instructions which reduces the language demands for participants. The Leiter-3 only requires the administration of four subtests to measure an individual's NVIQ, thus we used the Leiter-3 composite score (*M* = 100, *SD* = 15) when participants did not have a Raven's CPM or SPM+ score. The composite scores for the Raven's and the Leiter-3 were highly correlated (*r* = .72). For the Leiter-3, internal consistency reliability coefficients ranged from .71 to .95—the authors considered this reasonable for research (Roid et al., 2013). Test–retest reliability coefficients ranged from .74 to .86 (Roid et al., 2013). Concurrent validity was ascertained by examining the correlations between the Leiter-3 and other psychometrically sound cognitive measures. For example, the G*f* subtest of the Woodcock–Johnson III (WJ-III) and the five Leiter-3 cognitive scales were significantly correlated (*r* = .39–.78; Roid et al., 2013). The Leiter-3 was also validated against the previous version, Leiter-R (*r* = .78; Channell et al., 2015). Given that the Raven's and Leiter-3 assessments have low language demands, they were ideal measures of G*f* for individuals who may experience language difficulties.

Language

We captured participants' oral language skills with the Formulated Sentences subtest from the *Clinical Evaluation of Language Fundamentals, Fifth Edition* (CELF-5; Wiig et al., 2013).

The CELF-5 is a norm–referenced, standardized, comprehensive battery of language abilities (i.e., semantics, morphology, syntax, and pragmatics) for individuals aged 5 years to 21 years, 11 months. The Formulated Sentences subtest measured the participants' ability to create semantically and grammatically correct spoken sentences from different prompts. Thus, it provides an estimate of the participants' semantic, syntactic, and pragmatic language skills (Wiig et al., 2013). The Formulated Sentences subtest has strong internal consistency (r = .86). Test-rest reliability coefficients for the CELF-5 range from .83–.90 (Wiig et al., 2013). Furthermore, Coret and McCrimmon (2015) reported adequate to excellent concurrent validity between the CELF-5 and other language measures such as the Peabody Picture Vocabulary Test, Fourth Edition (r = .68–.95).

Executive Functioning

We captured a sense of participants' EF skills using the parent rating scale from the *Behaviour Rating Inventory of Executive Function 2* (BRIEF2; Gioia et al., 2015). The BRIEF2 (a standardized and norm-referenced test) includes three indices: Cognitive, behavioural, and emotional regulation, which combine into the Global Executive composite score and is reported as a T-score (M = 50, SD = 10). Higher scores indicate more challenges with EF. The BRIEF2 is suitable for children aged 5 to 18 years. Only the Parent Form, which consists of 63 items and takes approximately 10 minutes to complete (Gioia et al., 2015) was used. This form measures the following EF subdomains: Inhibition, self–monitoring, shifting, emotional control, initiation, working memory, planning, task–monitoring, and organization. The BRIEF2 has high internal consistency for the Parent Form Global Executive composite clinical sample (α = .96). The test-retest reliability coefficient was .79. Interrater reliability was established by creating numerous pairings across different raters. For the clinical sample, parent–parent reliability was .56, whereas for the norm sample, parent–parent reliability was .86. In addition, the manual (Gioia et al., 2015) also reported correlations between the BRIEF2 and other similar measures such as the Conners-3 Parent Form (r = .22–.56), Behavior Assessment System for Children-2 Parent Scale (r = .21-.66), and ADHD Rating Scale-IV (r = .50-.79).

Autistic Traits

Parents/guardians also completed the *Social Responsiveness Scale – 2nd Ed.* (SRS-2; Constantino & Gruber, 2012) to help capture the participants' autistic characteristics (i.e., to describe each participant's social and behavioral differences that are commonly associated with autism; e.g., expressive communication, social awareness, and RRBIs) and is normed for children aged 4 to 18 years. This School–Age Form contains 65 items and takes approximately 15 to 20 minutes to complete. The overall score is reported as a T–score (M = 50, SD = 10). The SRS-2 School–Age Form has strong internal consistency in clinical samples (α = .95) and good test–retest reliability from the original SRS ranging from .88 to .95 and interrater agreement (r = .77; Constantino & Gruber, 2012; see also Bruni, 2014). Content validity was established by expert reviewers across several fields (e.g., education and psychology; Bruni, 2014). Furthermore, for concurrent validity, Bruni (2014) reported moderate to high correlations for the School–Age Form against other measures such as Children's Communication Checklist (Bishop, 1998) and the Social Communication Questionnaire (r = .53; Channell et al., 2015; Rutter et al., 2001). According to the SRS-2 manual, a score greater than or equal to 60 indicates that the child has autism. Since all parents reported that their child had a formal diagnosis of autism, and since I was solely interested in describing the participants' autistic traits, I did not exclude participants based on their SRS-2 score. There were three participants in the sample with SRS-2 scores of 41, 51, and 52.

Procedure

To gather information on the variables of interest, it was initially planned that the testing would be conducted in up to eight sessions, with no session lasting longer than 60 minutes. Participants' parents were given a $10.00 gift certificate for their child's participation at the end of each testing session. Once the testing was completed, parents received an individualized written summary of their child's standardized test results. The study involved the completion of several measures, including SRS-2, Raven's SPM+ or CPM, CELF-5, KeyMath-3 DA^{CDN}, and BRIEF2. Rating scales (i.e., SRS-2 and BRIEF2) were generally completed by the parents in the first session. Two research assistants scored each measure to ensure consistency and accuracy and any discrepancies between raters were resolved by consensus. Data collection was spread out over multiple dates for each participant to accommodate the number of variables being measured and the availability of materials. We limited each session to 60 minutes to minimize testing fatigue. Participants completed the measures (i.e., KeyMath-3 DA^{CDN}, Raven's or Leiter-3, CELF-5, BRIEF2, and SRS-2) within 18 and 583 days (M = 161.45, SD = 143.02, Mdn = 116). The research design, including the sampling method, was approved by the University of Alberta's internal research ethics board (Pro00058795) before data collection commenced.

Analysis

First, I ran descriptive statistics (Table 3) summarizing the mean differences as well as analyzing the shape and spread of the distribution across all variables of interest.

Research Question 1: To answer the first research question, my sample was divided into three mathematical ability groups based on their performance on the KeyMath-3 DA^{CDN} Basic Concepts and Applications composite scores. To explore the relative proportions of autistic youth who were high– and low–achieving compared to expected rates in the general population, I conducted a chi–square goodness of fit test, which is an overall test for detecting relationships between two categorical variables: Mathematical ability group (high, average, low) versus diagnostic category (autistic, non–autistic). Initially, our intention was to splice our sample into five ability groups. However, if I had split my small sample into five ability groups, there would not have been at least five expected frequencies in each group, thus violating the chi–square assumption, which states that all expected counts should be 5 or greater. Therefore, I instead categorized the participants' mathematics scores into three ability groups:

1. High–achieving (SS $\geq$ 116);
2. Average (SS = 85-115); or
3. Low–achieving (SS $\leq$ 84).

Under the null hypothesis (H_0), the number of autistic participants in each of my three mathematical ability groups is the same as the expected number in each ability group according to the norms of the test (Connolly, 2008). If the alternative hypothesis (H_A) is true, I reject H_0 because my sample seems to have a significantly higher proportion of autistic youth whose scores fall within the low– and/or high–achieving range in mathematics compared to the expected proportion of students who would score as low– and/or high–achieving based on the normal distribution underlying these assessments.

Research Question 2: To examine the relationships between the participants' mathematical abilities and several individual characteristics, I first ran correlation analyses between all variables (i.e., age, autistic characteristics, G*f*, expressive language, EF, KeyMath-3 DA^{CDN} Basic Concepts, and KeyMath-3 DA^{CDN} Applications). Secondly, I investigated the unique contributions of G*f*, expressive language, and EF in predicting participants' scores on the Basic Concepts composite, above and beyond the contributions of the previous predictors using hierarchical regression analysis. Given the consistent empirical evidence for G*f* and mathematics achievement in non–autistic individuals (i.e., Cormier et al., 2017; McGrew & Wendling, 2010; Taub et al., 2008), G*f* was entered into the regression model first, then expressive language in the second model, and EF in the third model. This approach allowed me to see the unique contributions of expressive language and EF in predicting participants' Basic Concepts scores while G*f* is held constant in the model. All statistical analyses and visuals were generated using IBM SPSS Statistics (Version 29) and JASP (Version 17).

Results

Descriptives

33 autistic AMAB (*n* = 31) and AFAB (*n* = 2) aged 5–16 years (*M* = 9.85, *SD* = 3.49) participated in the study and completed several assessments to measure G*f*, expressive language, EF, autism traits, and mathematical ability. The means, standard deviations, minimum and maximum values, and statistics to describe the data set for KeyMath-3 DA$^{\mathrm{CDN}}$ Basic Concepts and Applications are presented in Table 3.

Autistic trait scores ranged from 41 to 90 (*M* = 75.79, *SD* = 11.31). Based on cut-off scores from the SRS-2 manual (Constantino & Gruber 2012), most of the participants fell in the 'severe' range regarding their social and behavioural differences. EF scores ranged from 40 to 83 (*M* = 69.82, *SD* = 9.20). Based on the cut–off scores from the BRIEF2 manual (Gioia et al., 2015), most of the participants fell in the 'potentially clinically elevated' range suggesting they may have EF challenges. The autistic traits and EF distributions were negatively skewed; however, the skew was within acceptable limits of normality (Table 3; West et al., 1995). For G*f*, scores ranged from 70 to 147 (*M* = 106.76, *SD* = 20.27), suggesting that most of the participants had average G*f* (15.2% [*n* = 5] of participants had a G*f* score of 130 or more). The mean of participants' expressive language scaled scores was slightly below the norm of the test, but still fell within the average range (*M* = 8.18, *SD* = 2.78), with scores ranging from 4 to 15. Given that most language scores ranged between average to low average, the language distribution was positively skewed (Table 3); however, again within acceptable limits (West et al., 1995).

Since my primary research question focused on exploring the diverse mathematical abilities of autistic children and identifying the prevalence of those with below or above-average skills, I did not exclude any participants based on their mathematical scores. Overall, my sample of autistic youth demonstrated average mathematics achievement for both KeyMath-3 DA^{CDN} Basic Concepts (*M* = 102.91, *SD* = 25.65) and Applications (*M* = 100.25, *SD* = 24.67). However, their mathematical abilities nonetheless ranged from *Extremely Low* to *Extremely High* for Basic Concepts (57–145 with 21.2% [*n* = 7] scoring 130 or more) and Applications (55–145 with 17.9% [*n* = 5] scoring 130 or more). As shown in Table 3, the kurtosis and skewness for Basic Concepts and Applications are within acceptable limits (West et al., 1995).

Table 3

Descriptive Statistics for all Variables

Variable	*N*	*M (SD)*	Range	Kurtosis	Skewness
Age	33	9.85 (3.49)	5–16	-0.74	0.62
Autistic Traits	33	75.79 (11.31)	41–90	2.17	-1.42
Fluid Reasoning	33	106.76 (20.27)	70–147	-0.34	0.42
Expressive Language	33	8.18 (2.78)	4–15	-0.01	0.66
Executive Functioning	33	69.82 (9.20)	40–83	2.37	-1.22
Basic Concepts	33	102.91 (25.65)	57–145	-0.92	0.29
Applications	28[A]	100.25 (24.67)	55–145	-0.46	0.23

Note. [A] Descriptive statistics for the subgroup (*n* = 28) that completed the Applications subtests can be found in Appendix A.

The KeyMath-3 DA^{CDN} Basic Concepts composite is comprised of five domains: Numeration, Algebra, Geometry, Measurement, and Data Analysis/probability. While I did not statistically compare the means, Table 4 presents the means, standard deviations, minimum and maximum values, and statistics to describe normality across the mathematics domains. Overall, my sample of autistic youth demonstrated average mathematics achievement across all domains, scoring slightly higher in Numeration and Data Analysis/probability with scores ranging between 4 and 19. The lowest scores observed were in Geometry ranging from 1 to 19. The kurtosis and skewness for all domains are within acceptable limits (West et al., 1995).

Table 4

Descriptive Statistics for the Five KeyMath-3 DA^{CDN} Domains

Variable	*M (SD)*	Range	Kurtosis	Skewness
Numeration	11.24 (4.72)	4–19	-0.98	0.45
Algebra	10.97 (4.86)	2–19	-1.08	0.39
Geometry	10.70 (4.31)	1–19	-0.10	0.26
Measurement	10.06 (5.03)	2–19	-0.94	0.27
Data Analysis and Probability	11.03 (4.84)	4–19	-1.10	0.41

Pearson Correlation Analyses

Next, I explored the strength of the relationships between the five subtests that comprise the KeyMath-3 DA^{CDN} Basic Concepts composite (i.e., numeration, algebra, geometry, measurement, data analysis/probability) to explore the extent to which the domains were correlated with one another. As Table 5 demonstrates, all domains were significantly and strongly correlated with each other (*r*s = .72–.93). The strong relationships between these five subtests suggest that each individual's performance on one mathematical subtest was highly similar to their performance on the others, and therefore it would be redundant to look at the proportions of low– and high–achieving participants across each subtest. Consequently, I ran my chi–square analyses at the level of the mathematics composite scores.

Table 5

Pearson's Correlations for the Five KeyMath-3 Domains

Variable	*N*	*M*	*SD*	1	2	3	4	5
1. Numeration	33	11.24	4.72	—				
2. Algebra	33	10.97	4.86	$.93^{***}$	—			
3. Geometry	33	10.70	4.31	$.72^{***}$	$.74^{***}$	—		
4. Measurement	33	10.06	5.03	$.89^{***}$	$.90^{***}$	$.78^{***}$	—	
5. Data Analysis and Probability	33	11.03	4.84	$.92^{***}$	$.90^{***}$	$.77^{***}$	$.90^{***}$	—

Note. Statistical significance: $^{***}p < .001$

I also explored the strength relationships between mathematical ability at the composite level (Basic Concepts and Applications) and individual traits (G*f*, expressive language, EF, autistic traits, and age). As shown in Table 6, G*f* and expressive language were positively and strongly correlated with both composites. In comparison, EF had a moderate, negative correlation with Basic Concepts. Autistic traits seemed to have a small (but nonsignificant) relationship with mathematical ability yet were strongly correlated with EF. Last, age was not significantly correlated with any variables, which makes sense given the standardized tests are age–normed.

Table 6

Pearson Correlations: Strength of the Relationships Between All Variables

Variable	*n*	*M*	*SD*	1	2	3	4	5	6	7
1. Basic Concepts	33	102.91	25.65	—						
2. Applications	28	100.25	24.67	$.97^{***}$	—					
3. Fluid Reasoning	33	106.76	20.27	$.73^{***}$	$.74^{***}$	—				
4. Expressive Language	33	8.18	2.78	$.61^{***}$	$.67^{***}$	$.49^{**}$	—			
5. Executive Functioning	33	69.82	9.20	$-.36^{*}$	-.22	-.16	-.13	—		
6. Autistic Traits	33	75.79	11.31	-.24	-.04	-.11	-.08	$.72^{***}$	—	
7. Age	33	9.85	3.49	-.06	-.02	.16	-.02	.03	-.14	—

Note. Statistical significance: $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$

Chi–Square Analyses

KeyMath-3 DA^{CDN} Basic Concepts

As can be seen by the frequencies cross–tabulated in Table 7, there is a significant relationship between mathematical ability group (as measured by the Basic Concepts composite) and diagnostic group, X^2 (2, N = 33) = 9.46, $p < .01$, φ = .54. More specifically, there was a significantly higher proportion of autistic youth in my sample who were low–achieving in mathematics (21.21%) and/or high–achieving (33.33%) compared to the expected rates in the general population (15.76%).

Table 7

Chi–Square Results for KeyMath-3 DA^{CDN} Basic Concepts

Math Ability Group	Expected		Observed	
	n	%	*n*	%
Low Achieving	5.20	15.76	7.00	21.21
Average	22.50	68.18	15.00	45.45
High Achieving	5.20	15.76	11.00	33.33
$\chi^2(2)$	9.46^{**}			

Note. Statistical significance: $^{**}p < .01$

KeyMath-3 DA^{CDN} Applications

To conduct the chi–square analysis for the Applications composite, five participants had to be excluded because they did not complete the Applications subtests (see Appendix A for updated descriptives statistics on this subgroup). As can be seen by the frequencies cross-tabulated in Table 8, there is a significant relationship between mathematical ability group (as measured by the Applications composite) and diagnostic group, X^2 (2, $N = 28$) = 6.28, $p < .05$, $\varphi = .47$. More specifically, there was a significantly higher proportion of autistic youth in my sample who were low–achieving in mathematics (25%) and/or high–achieving (28.57%) compared to the expected rates in the general population (15.71%).

Table 8

Chi–Square Results for KeyMath-3 DA^{CDN} Applications

Math Ability Group	Expected		Observed	
	n	%	*n*	%
Low Achieving	4.40	15.71	7.00	25.00
Average	19.10	68.21	13.00	46.43
High Achieving	4.40	15.71	8.00	28.57
$\chi^2(2)$	6.28^{*}			

Note. Statistical significance: $^{*}p < .05$

Hierarchical Multiple Regression

Checking Assumptions in Regression

The assumptions for multiple regression analysis were tested and met in this study (see Appendix B). The predictors showed variability above zero, indicating non–zero variance. The relationships between the predictors and outcome variables were linear, indicating linearity. Each participant's data was unique, satisfying independence. The Durbin–Watson statistic showed no autocorrelation among the residuals, indicating independent errors. The residuals showed no trend or pattern, satisfying homoscedasticity. The standardized residuals histogram and the normality probability plot both indicated that the residuals in the model adhere to a normal distribution. The probability plot displayed points with no significant deviations from the line, thus fulfilling the assumption of normality. There was no significant multicollinearity among the predictor variables, indicating no presence of collinearity within the data.

Regression Results

I used a hierarchical multiple regression (to explore the extent to which participants' G*f*, expressive language, and EF skills accounted for unique variance in participants' mathematical ability Table 9). Given my small sample size along with the very strong correlation ($r = .97$) between the KeyMath-3 Basic Concepts and Applications composites (as shown in Table 6), the Basic Concepts composite was chosen as the primary outcome variable as it had the most data available. Language and EF skills were of particular interest and the aim was to investigate their independent contribution above and beyond G*f*. As such, the first model included G*f* alone, followed by language, and then EF.

Model 1 showed that G*f* (as measured by the Raven's Progressive Matrices or Leiter-3) alone accounted for 53% of the variance in participants' Basic Concepts scores, $R^2 = .53$, F(1,

31) = 35.56, $p < .001$, 95% CI [.61, 1.24]. Model 2 demonstrated that expressive language (as measured by the CELF-5 Formulated Sentences subtest) accounted for a small (β = .33), but significant proportion of the variance in Basic Concepts scores, increasing the total amount of variance explained by the model to 62%, $R^2 = .62$, $F(2, 30) = 24.27$, $p < .05$, 95% CI [.62, 5.50]. Model 3 revealed that EF skills (as measured by the parent report of the BRIEF-2) also explained a small (β = -.23), but significant proportion of the variance in Basic Concepts scores, increasing the total amount of variance explained by the model to 67%, $R^2 = .67$, $F(3, 29) = 19.37$, $p < .05$, 95% CI [-1.25, -.01].

Table 9

Hierarchical Regression Model Summary

	Variable	*B*	95% CI for *B*		*SE B*	β	R^2	ΔR^2
			LL	*UL*				
Model 1							.53	.53***
	Constant	4.14	-30.22	38.51	16.85			
	Fluid Reasoning	0.93	.61	1.24	0.16	.73***		
Model 2							.62	.08*
	Constant	0.94	-30.84	32.73	15.56			
	Fluid Reasoning	0.72	.39	1.06	0.16	.57***		
	Expressive Language	3.06	.62	5.50	1.19	.33*		
Model 3							.67	.05*
	Constant	49.88	-7.16	106.93	27.89			
	Fluid Reasoning	0.68	.36	1.00	0.16	.54***		
	Expressive Language	2.91	.59	5.23	1.14	.32*		
	Executive Functioning	-0.63	-1.25	-.01	.30	-.23*		

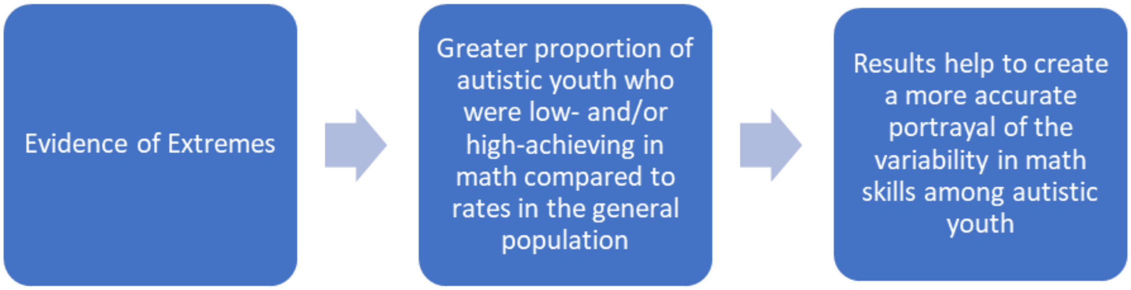
Note. Statistical significance: $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$

Discussion

Brief Overview of the Study

The aims of the current study were twofold: First, to explore the relative proportions of autistic youth who demonstrated above or below average (±1 *SD* of the norm) performance on standardized tests of mathematical ability. Second, to learn what underlying cognitive abilities predict mathematical ability among autistic youth by exploring the relative contributions of G*f*, expressive language, and EF. To achieve these aims, 33 participants completed measures assessing mathematical ability, G*f*, and expressive language. The participants' parents also completed rating scales to measure autistic traits and executive functioning skills.

Aim 1: Evidence of Extremes



We initially sought to understand the mathematical profiles of autistic youth by looking at their performance across each of the five mathematics domains (e.g., algebra) since most prior studies have focused on global mathematical abilities of autistic children, with few exploring mathematical skills at the domain–level (Titeca et al., 2015). However, as expected, the five domains are strongly correlated with each other (*r*s = .72–.93), which makes sense given that the developers of the KeyMath-3 DA$^{\text{CDN}}$ combined these domains to comprise the Basic Concepts composite. Nevertheless, it was interesting that the correlations between some of the subtests were almost perfect (such as the Numeration and Algebra [*r* = .93]), whereas the strength of the relationship between other pairs were weaker (e.g., Geometry and Algebra [*r* = .74]). Overall, these analyses suggest that the autistic youth in our sample tended to perform consistently across domains. To determine the relative proportions of low– and high–achieving mathematical ability, participants were grouped into three categories for both Basic Concepts and Applications composites: Low–achieving, typically achieving, and high–achieving. Regarding the Basic Concepts composite, we found that there were a significantly higher proportion of autistic youth who were low–achieving (21.21%) and high–achieving (33.33%) compared to the expected rates in the general population (15.76% for each). For the Applications composite, we also found a significantly higher proportion of our autistic sample that were low–achieving (25%) and high–achieving (28.57%) in mathematics compared to the expected rates (15.71%). My results align with prior studies (i.e., Bullen et al., 2020; Oswald et al., 2016) that suggest weaknesses in mathematics is prominent among autistic youth. Although, on average, there were more high-achieving than low-achieving autistic youth in my sample, my study did not have the power to confirm whether or not these differences occurred by chance. Therefore, future researchers should consider exploring this question with a larger sample size. Given that autistic youth are more likely to have either strengths or weaknesses in mathematics, it remains unclear how a shared diagnosis can lead to such distinctive mathematical ability profiles. Profiles that differ greatly between those who share the same diagnostic label as well as in comparison to their non-autistic peers.

Autistic Traits and Mathematical Ability

Given that having an autism diagnosis seems to increase the likelihood of both mathematical strengths and mathematical weaknesses, the core symptoms of autism may play a role in predicting students' mathematical abilities. For example, Oswald et al. (2016) included a dichotomous predictor to denote 'having' or 'not having' a diagnosis of autism in their regression analysis of predictors of mathematical problem–solving abilities. They found that a diagnosis of autism was a significant predictor of lower mathematical problem–solving scores, but this predictor accounted for the smallest amount of variance in the model. Oswald and colleagues (2016) did not explicitly interpret this finding aside from suggesting a possible relationship between autism and inattention, although inattention was not directly measured. On the other hand, Miller and colleagues (2017) included a measure of autistic traits that generated a continuous variable that quantified severity. They found that participants who were rated as having more autistic traits had lower mathematics scores. However, when IQ was added to their models, autistic traits were no longer predicting any unique variance in participants' mathematics scores. Like Oswald and colleagues (2016), Miller and colleagues (2017) used a measure of autistic traits that amalgamated both core symptom domains. Although it has been suggested that social communication deficits can be disruptive to mathematics learning (Miller et al., 2017), it is unclear whether increased engagement in RRBIs positively or negatively affects mathematics learning. However, in my study, the correlations between autistic traits (as measured by the SRS-2) and the KeyMath-3 DA^{CDN} Basic Concepts and Applications composite scores were small and not significant (*r*s = -.24 and -.04, respectively), suggesting that autistic traits (at least as measured by the SRS-2) did not account for much of the variability in mathematical skills in my sample. The SRS-2 has its limitations, for example, there is an under–representation of some autistic traits such as sensory sensitivities and physical repetitive behaviours (English et al., 2021). Future researchers might consider measuring other autistic traits that may impact mathematical abilities, such as WM. Given the previously mentioned meta–analyses describing EF weaknesses in autistics, one can argue there is a consensus among researchers that autistic individuals tend to have WM challenges. Furthermore, there are mixed findings reported on how

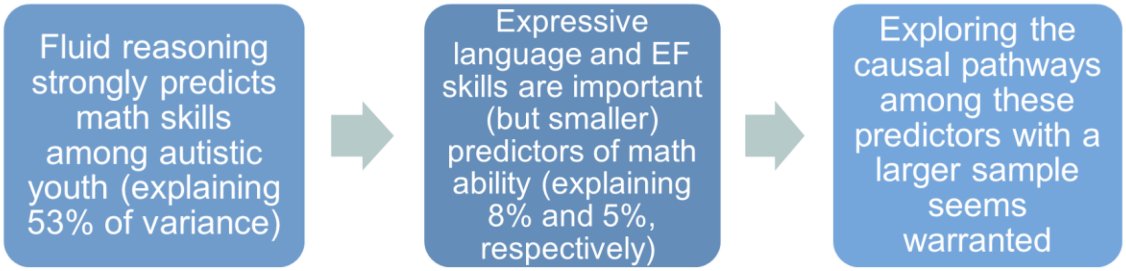
EF skills impact the mathematics achievement of autistic youth. Considering this, WM difficulties and mathematics may be an important avenue for further investigation. Researchers should consider measuring WM using a direct assessment (e.g., NIH Toolbox for Children, 2013) for a potentially more accurate and nuanced measure of the skill rather than a parent report.

Impact and Significance: Evidence of Extremes

According to the prevailing view in popular culture, autistic traits are believed to lead to exceptional mathematics achievement, a myth that has been propagated in popular media. This widespread misconception (Draaisma, 2009) disregards the heterogeneity of mathematical abilities within the autistic population. In fact, in a qualitative study with 37 participants with and without experience of autism (i.e., university students and adults), John and colleagues (2017) found that many endorsed the myth that all autistic individuals have special talents or exceptional skills. My study highlights the variability of mathematical performance among autistic youth and emphasizes that exceptional mathematical ability is not a defining characteristic of autism. The high proportion of low–achieving youth in this study suggests some autistic individuals may likely benefit from targeted interventions to improve mathematical skills. In addition, the high-achieving group may provide insights into the strengths and abilities of autistic youth and inform mathematics interventions which leverage these strengths.

The prevalence of stereotypical beliefs associating exceptional mathematical abilities with most autistic students can pose a significant barrier for these students in accessing the essential academic support they need. When autistic students encounter challenges in mathematics, they might be unfairly perceived as ‘being unwilling to try’ if they fail to meet the expected mathematical benchmarks. Consequently, educators may overlook true mathematical weaknesses among autistic youth, attributed to a lack of *perceived* effort from the student, which might mean that the student misses the opportunity to receive remedial instruction. The perspective outlined above can have lasting repercussions for autistic students' support, as poor mathematics performance has been linked to lower self–esteem and often limits career development opportunities (Benbow et al., 2000; Peters et al., 2013; Rodriguez et al., 2013). As mathematics knowledge is often regarded as an important skill for daily living skills (e.g., budgeting) and future success (Chen et al., 2019; May et al., 2013), the implications of not receiving adequate support in this area can be significant for autistic students. This view can also limit the availability of funding for intervention programs that can be critical for their mathematics development. Our study's findings challenge current lay perspectives on autism, and it may inform parents and educators of the variability of mathematics achievement in the autistic population and the probability that many autistic youths are likely to have low– or high–achieving mathematical abilities.

Aim 2: Predictors of Mathematical Ability: One Diagnosis, Two Outcomes?



Fluid reasoning strongly predicts math skills among autistic youth (explaining 53% of variance)

Expressive language and EF skills are important (but smaller) predictors of math ability (explaining 8% and 5%, respectively)

Exploring the causal pathways among these predictors with a larger sample seems warranted

Thus, researchers will need to explore the relationship between other factors and mathematical ability to begin to untangle the question of how a diagnosis of autism leads to mathematical strengths for some autistic youth and weaknesses for others? The present study investigated the role of three individual characteristics (i.e., G*f*, expressive language, and EF) in predicting mathematical ability among my sample of autistic youth. To understand the strength of the relationships between individual characteristics and mathematics, I conducted correlation analyses. This revealed the Basic Concepts and Applications composites (respectively) were strongly correlated with G*f* (*r*s = .73 and .74*)* and expressive language (*r*s = .61 and .67). In contrast, these two mathematics composite scores showed only a small–to–moderate correlation with parent–reported EF (*r*s = -.36 and -.22). Using Basis Concepts as the outcome variable in a hierarchical regression analysis, G*f*, expressive language, and EF all uniquely contributed to the model. However, G*f* accounted for the most variance (53%) in mathematical ability scores. In comparison, expressive language and EF accounted for 8% and 5% of the model variance, respectively.

Autism, G*f*, and Mathematical Ability

My result that G*f* accounted for the most variance in mathematical ability scores is consistent with previous literature emphasizing the relationship between G*f* in mathematical ability in autistic (Oswald et al., 2016) and non–autistic (Green et al., 2017; Peng et al., 2019) samples. G*f* provides the foundations for abstract reasoning and problem–solving which are considered core skills to be successful in mathematics (McGrew & Wendling, 2010).

The hypersystemizing theory proposes that autistic individuals tend to have above-average levels of systemizing; the definition of which seems to include both G*f* strengths coupled with an innate drive required to recognize patterns and generate underlying rules to solve problems (Baron–Cohen & Lombardo, 2022; Baron–Cohen et al., 2007). For example, Baron–Cohen and Lombardo (2022) defined systemizing as, "... the function of the SM [systemizing mechanism] is to identify laws, rules, and/or regularities that govern a system, so as to understand how that system works and predict what it will do" (p. 346). This definition clearly highlights the importance of G*f* to Baron–Cohen's notion of systemizing. Baron–Cohen and

Lombardo (2022) suggest that RRBIs—common features of autism—are likely driven by hypersystemizing. This particular strength in identifying laws, rules, and regularities is vital for quantitative reasoning, a key aspect of mathematics. Therefore, the hypersystemizing theory may explain the increased prevalence of high–achieving autistic individuals in my sample. However, if true, this does not help us understand those autistic students who struggle in mathematics (discussed in the next section).

A neuro–affirming perspective of passionate interests (and specifically RRBIs) highlights that passionate interests are often areas of strength for people with autism. Many autistic children describe passionate interests as a vital part of how they define themselves (Winter–Messiers, 2007). As students with autism spend time engaging in their special interests, they are also engaging in more enriching learning experiences (Wood, 2021). Klin and colleagues (2007) detailed the numerous ways that children engage with restricted sets of interests, including collecting information and developing expert knowledge in a variety of topics. Attwood (2008) also explained that passionate interests involve constantly engaging in processes of categorization and calculation, such as collecting sports statistics. In this way, passionate interests may be a facet of RRBIs that provide autistic children with rich mathematics learning experiences.

Two theoretical perspectives of how all children acquire fundamental mathematical skills may help to clarify how RRBIs may provide more opportunities for the development of mathematical expertise among autistic youth. First, Schwank and Schwank (2015) emphasized the importance of predictive–logical reasoning, which is “a type of inferential logical thinking that establishes relations by focusing on similar or identical components of objects,” (p. 773) as a key skill underlying the development of mathematical reasoning. Students who are intensely engaged in a passionate interest may also be regularly engaging in processes of categorization and systemizing—processes which may mimic predictive-logical reasoning tasks. This regular engagement presents many opportunities for practicing these skills, which may further support autistic students' mathematical ability development.

Second, Byrnes and Miller's (2007) proposed the opportunity–propensity model to explain key predictors of high school mathematics achievement. The opportunity–propensity model highlighted the importance of both opportunities for learning within a particular domain and an individual's innate propensity for learning in that domain. Given that up to 95% of students with autism describe having passionate interests (Turner–Brown et al., 2011), RRBIs may help to explain why some autistic students become excellent mathematicians. Students engaging in passionate interests more frequently and intensely are encountering more experience with categorization and systemizing, two tasks which engage predictive–logical reasoning. Additionally, one might argue that these students also have the propensity to learn mathematics more readily due to the intensity of their special interest, which involves processes similar to mathematical reasoning. To understand the relationship more clearly between RRBIs and mathematical ability development, researchers must first develop more specific measures focused exclusively on passionate interest engagement. In this way, future studies can assess whether special interest engagement contributes to mathematical ability development. Nevertheless, given some autistic students excel in mathematics at school, I will now detail some recommendations for teachers about how to support autistic students who excel in mathematics.

Evidence–Informed Strategies for Supporting Talented Autistic Youth in Mathematics

A very recent systematic review (Gelbar et al., 2022) reported that the research on evidence–based educational strategies for gifted autistic students is limited and to my knowledge, none exist in supporting gifted autistic students in mathematics. Some research has suggested that autistics students with IQs in the gifted range are often provided ineffective educational support (Assouline et al., 2009; Rubenstein et al., 3013). In a study with 59 gifted autistic children and adolescents, Assouline and colleagues (2012) found that participating in talented and gifted programs was significantly and positively correlated ($r = .36$) with mathematics, reading, and oral language achievement; their results revealed that subject and grade acceleration (e.g., placing a student in a higher grade or subject than their age) was not correlated with achievement. This finding suggests that gifted autistic students may benefit from participating in academic enrichment programs. Bianco and colleagues (2009) recommended that gifted autistic students receive a dually differentiated curriculum (i.e., addressing both the unique academic challenges they may experience and their academic strengths), recognize and integrate their passionate interests into the curriculum, and adopt a strengths–based approach to curriculum planning and pedagogical approaches. Similarly, Rubenstein and colleagues (2013) explored ten curriculum models designed to support high–achieving students in general, one which was geared to educating mathematically talented non–autistic students – *Project* M^3*: Mentoring Mathematical Minds* (Gavin et al., 2007). Rubenstein and colleagues (2013) identified five key features/similarities across the different curriculum models:

- Differentiated instruction (i.e., adapting the curriculum to meet the student's needs),
- Promote communication (i.e., encouraging the student to agree/disagree, rephrase comments, and elaborate on others' ideas),
- Facilitate problem–based learning (i.e., implementing authentic, real–world problems),
- Encourage the development of complex thinking skills (i.e., critical thinking activities with explicit instruction and question prompts), and

- Nurture creativity by using the student's passionate interests.

Gavin and colleagues (2007) provide the following mathematics unit example: If students were learning about place value and they had a passionate interest in archeology, the teacher could simulate an archeological dig for the students to explore numerical markings on stones (e.g., patterns, groupings). An acceleration activity could be encouraging students to learn about bases beyond base–10, such as the base–3 numeration system. Each lesson can include a 'Think Beyond Card' which challenges the students to expand on their knowledge through reasoning. These five components of gifted programs have been recommended for gifted autistic students as well (Rubenstein et al., 2013). Overall, researchers have suggested that gifted autistic students may benefit from academic enrichment programs that are modified to meet the strengths and needs of this population, such as providing inquiry–based learning activities and including students' special interests for engagement. In the next section, I will explore possible relationships between autism, language, and mathematical ability.

Autism, Language, and Mathematical Ability

Researchers have found relationships between different aspects of language and mathematical ability in unselected samples of students; however, this relationship appears to be less clear in autistic youth. Existing autism research in this area is limited, with some researchers reporting that language was not a significant predictor of mathematical ability (i.e., Bullen et al., 2020), while others report associations between the two domains (i.e., Chen et al., 2019). It was unexpected that language only accounted for a small (but significant) proportion of the variance in the mathematical skills of my autistic participants for two reasons: Given the strong relationship between language (i.e., mathematics vocabulary and language comprehension) and mathematical ability in the non–autistic population, one may have assumed that a similar relationship would exist with autistic youth. Second, on average autistic youth experience language difficulties (i.e., Kwok et al., 2015), so it is plausible that this challenge would hinder their mathematics achievement. Nevertheless, there are two potential explanations for my unexpected findings: While participants with low, average, and high language scores were included in the study, the small sample size resulted in a limited range of language scores, with the majority falling in the low to average ranges. Consequently, this restricted my ability to investigate the impact of language ability on mathematical skills in autistic youth with high language scores. Second, my results were also impacted by my choice to use a single subtest of the CELF-5 as a proxy of expressive language ability (due to missing data). Future researchers should consider using a holistic measure of language ability – such as the Core Language Score from the CELF-5 – to quantify how specific language subskills may be related to different mathematical abilities. While my study did not find that language played a large role in my participants' mathematical ability, weaker language skills nevertheless may still play an important role in explaining why some autistic youth struggle in mathematics. As such, the next section provides recommendations for teachers about how to best support autistic youth with language challenges in mathematics.

Evidence–Informed Strategies for Supporting Autistic Youth with Language Challenges in Mathematics

For autistic students who require less complex language in mathematical problems, a structured format (Spooner et al., 2017) such as task analysis and explicit instruction were found to be beneficial pedagogical strategies for mathematical concepts (Root et al., 2021). Task analysis involves teaching students to break down tasks into discrete steps and providing the student with individualized instructions for each step until they can complete the task on their own (Collins, 2012), thus promoting independence (McConomy et al., 2021). This approach can support students in solving word problems by having them break down the problem into manageable parts. As a simple example, the task analysis for solving a mathematical word problem might be to “identify the type of problem they are solving, what is known and unknown, and then make and carry out a plan for arriving at a solution” (McConomy et al., 2021, p. 415). Students can be explicitly taught how to use the task analysis to solve similar problems independently. This strategy may support a student with language challenges because they can be encouraged to break down text–heavy mathematics problems into smaller components. Explicit or systematic instruction involves scaffolding student learning, demonstrating the skill, and providing practice opportunities and corrective feedback (Archer & Hughes, 2011). In fact, explicit instruction is often a component in task analysis due to the teacher explicitly modelling the steps or skills in a task analysis. Furthermore, pre–teaching and building students’ vocabulary will support their acquisition of information from general to mathematics–specific language and support their learning as academic language increases in complexity throughout schooling (Alberta Education, 2010). Teachers might model how to use specific mathematical vocabulary in a problem and encourage students to keep a list of mathematical–related words (Alberta Education, 2010). Teachers can support students’ reading comprehension by teaching and modelling the strategy, ‘Read, Ask, Put in my own words’. This strategy may be helpful for students solving mathematical word problems by breaking the text into parts and finding key information (Alberta Education, 2010). Lastly, teachers can support language challenges in mathematics by encouraging students to engage in number visualization (i.e., mental representations), spatial visualization (i.e., describing relationships between objects), and measurement visualization (i.e., knowing when to measure versus estimate; Alberta Education, 2010). Visual aids (e.g., manipulatives such as base–10 blocks) can be a beneficial tool for students who are learning new vocabulary or experiencing language difficulties, as they replace words with pictorial representations that may facilitate their understanding and make the mathematical content more accessible.

Autism, EF, and Mathematical Ability

Autistic individuals often face greater difficulties with EF in comparison to their non-autistic counterparts (i.e., Demetriou et al., 2018). When considering mathematics, some researchers have found that various EF subdomains are correlated and predictive of autistics' mathematics achievement (Bullen et al., 2020; Chen et al., 2019; St. John et al., 2018). Therefore, I hypothesized that EF would play a significant role in predicting my participants' mathematical abilities. However, my results suggested that EF skills played a small (albeit significant) role in predicting the mathematical achievement of autistic youth above and beyond the contribution of G*f*. One possible explanation for this unexpected finding could be that certain EF subskills may be more strongly related to mathematical ability than others and using a global measure of EF (as I did in this study) may have masked meaningful relationships between specific EF subdomains and mathematical ability. In particular, it may be important to further explore the role of WM on autistic youths' mathematics achievement. As previously mentioned, a literature review on WM and autism reported autistic children had similar WM profiles to children with an SLD in mathematics (e.g., implementing fewer and more rudimentary strategies; Kercood et al., 2014). Furthermore, researchers have shown that WM significantly predicted low or high mathematics performers among samples of autistic youth (Chen et al., 2019, Bullen et al., 2022). These findings indicate that most likely, there link between WM and mathematics achievement in autistic individuals. In my future research, I would choose a direct assessment of EF skills such as the Cognitive Assessment Battery (CAB) PRO (Nordlund et al., 2011), to measure the different EF subdomains and their impact directly and accurately on mathematics achievement. In light of the association between EF and mathematics achievement, the next section offers some recommendations for teachers on how to best support autistic students with EF challenges in mathematics.

Evidence–Informed Strategies for Supporting Autistic Youth with EF challenges in Mathematics

Researchers have shown how EF supports the acquisition of mathematical concepts and relations between different EF subdomains and mathematical skills in non–autistic (Cragg & Gilmore, 2014) and autistic samples (Bullen et al., 2020). For example, WM may support arithmetic skills and understanding quantitative relationships (Lee et al., 2009) while CF may be crucial for successfully transitioning between different procedures while solving complex mathematical problems (Cragg & Gilmore, 2014). Several evidence–based practices can support autistic students' EF skills thereby potentially improving their mathematics. In particular, the use of task analysis, graphic organizers, explicit instruction, and schema–based instruction may reduce a student's cognitive load and support their WM to solve mathematical problems (Siregar, 2023; Smith et al., 2016).

A systematic review by Root and colleagues (2021) describes several evidence–based practices—based on the Council for Exceptional Children's criteria (2014)—to teach autistic students to solve mathematical word problems. The studies included in this systematic review used these strategies in combination with each other and never in isolation. The first two—task analysis and explicit instruction (i.e., scaffolding their student's learning through guided practice and feedback; Smith et al., 2016)—were described earlier (see p. 75) and can also be used to support EF challenges. The system of least prompts is an approach where the teacher provides the student with prompts from the least to most assistance (Collins, 2012), such as starting with a verbal prompt, then moving to a specific verbal prompt, and lastly a model prompt (Root et al., 2021). Offering a student a series of hierarchical prompts may support their WM and CF by assisting them in determining the appropriate operations or steps to solve mathematical problems. In addition, students can also use visual memory aids (e.g., graphic organizers, number lines, and sentence prompts; Smith et al., 2016) to see the positions of quantities and their interrelationships, reinforcing both their conceptual and procedural understanding (Ives & Hoy, 2003). For example, graphic organizers can assist students with filling out equations (Root et al., 2021). Technology–assisted instruction involves any type of technology to support learning (e.g., calculators, iPads). For example, students who struggle with the automaticity of math facts may have more difficulty solving complex mathematical problems. Using a calculator to solve more basic mathematical problems can reduce efforts on their WM, allowing them the opportunity to solve the complex problem. Smith and colleagues (2016) also suggest teaching skills in isolation, starting with simple concepts so that students gain foundational knowledge. They can then be encouraged to integrate them with pre–existing skills.

To summarize, strategies that support strengths or weaknesses in G*f*, language and EF may be important for supporting the development of mathematical ability among both autistic and non–autistic students. I have also tried to offer important insights for assisting autistic students in overcoming barriers that may impact their mathematics achievement. Understanding the relationship between individual characteristics and mathematics achievement can equip teachers with practical approaches to facilitate optimal mathematical skill development in autistic students.

Limitations

There are several limitations of the current study that must be addressed. First, participants completed the measures over a long period of time (15 to 586 days). This may pose a significant threat to the internal validity of this study. For some participants, changes in their personal life (e.g., receiving tutelage for mathematics during the study) may have influenced their scores taken on later assessments. Furthermore, my study comprised of youth under the age of 17 who are uniquely susceptible to maturation. Over the course of months to years, the natural development of the child may influence their testing scores (e.g., EF develops rapidly under the age of 11). Therefore, comparing scores between tests taken at different time points could pose a threat to the study's internal validity.

Second, due to the small sample size, my study had limited statistical power to detect the effects of interest. Although it is not uncommon to have small sample sizes when studying clinical populations, a larger sample size would be necessary to fully explore the main questions in my study. Future research should consider recruiting a greater number of autistic participants when replicating this study to improve the study's statistical power.

Third, parents self–reported their child's autism diagnosis with the research team. My study would have been stronger if I had been able to independently confirm the participant's autism diagnosis, especially given that three of my participants had SRS-2 scores below the cut-off for autism (<60). For example, similar to the strategy used Mayes & Calhoun (2008), future researchers (with funds to do so) could consider having a registered psychologist conduct an autism assessment with prospective participants. This will ensure all participants in the sample have an official autism diagnosis and any co–occurring conditions. Given that the parents reported their child's diagnosis, there is the possibility that some participants in my sample may have been inaccurately identified which hinders the generalizability of the results to the autistic population.

Given that autism is a unique population, convenience sampling was conducted to recruit participants. This form of nonrandom sampling limits the generalizability from the sample (Johnson & Christensen, 2019) to the autistic population. In addition, this sampling procedure may result in self–selection bias which occurs when participants seek out a study and choose to participate on their own accord. This bias suggests that those who participate may differ from those who do not (e.g., the participant's family's motivation, interest, demographics). As a result, this bias may have threatened the external validity since the sample is not representative of the autistic population.

Finally, the study's generalizability is restricted by the limited diversity among my participants. For example, only 6% of our sample identified as AFAB (versus AMAB) and none identified as gender non–binary. Given that some have suggested links between gender and mathematical ability (e.g., Ayalon & Livneh, 2013; Contini et al., 2017), it may be important for future researchers to explore and compare the mathematical abilities of different gender subgroups. A second large oversight was that race and ethnicity were not captured during data collection. However, the general impression of the research assistants assigned to the project, was that most families were from white, Judeo–Christian backgrounds. This is problematic because autistic Black, Indigenous, and people of colour (BIPOC) are consistently under-represented in autism research (Jones et al., 2020). This lack of inclusion leads to a scarcity of information and resources to meet the needs of individuals who identify with these intersecting identities. To improve generalizability, future researchers should aim to intentionally recruit participants from diverse and marginalized backgrounds.

Future Directions

Researchers have primarily focused on autistics' arithmetic ability, neglecting the exploration of individual mathematics subdomains (e.g., algebra or geometry) and applied mathematical problem–solving skills (i.e., solving a mathematical problem without prior knowledge of the solution; Bae et al., 2015). With a greater focus on the arithmetic ability of autistic students, little is known about their abilities in these areas. This knowledge gap is concerning for two main reasons. Firstly, educational curricula in Western society typically include the learning of these specific subdomains. Secondly, teachers often expect students to be capable of solving mathematical word problems. Previous studies have primarily concentrated on the overall mathematical abilities of autistic children, with only a few examining their skills at the domain–level (Titeca et al., 2015). Additionally, success in different mathematics subdomains and word problem–solving may require different cognitive skills. Future studies should consider expanding on the current research by exploring the mathematics profiles of autistic youth across the subdomains and investigate the direct and indirect relationships of language (e.g., expressive and receptive) and EF (e.g., WM and CF) on word problem–solving ability while controlling for age, G*f*, and arithmetic ability.

Conclusion

Autistic individuals are often stereotyped as having exceptional mathematical abilities, which may lead to unrealistic expectations of their skills by others. This may result in disappointment for those who do not display exceptional abilities, as well as for their parents and teachers (Draaisma, 2009). Furthermore, it may dismiss the need for appropriate support for those who may find this area challenging. My study reveals that while a greater proportion of autistic youth are high–achieving in mathematics compared to the expected rates in the general population, a significant proportion also have weaknesses in mathematics. These results challenge existing stereotypes of autism and offer a more accurate depiction of the diverse range of mathematical skills within the autistic population. Additionally, this study highlights the significant contributions of G*f*, expressive language, and EF as predictors of mathematical ability and extends existing research. My findings highlight the importance of further understanding the role of these individual characteristics and provide avenues for further investigation into the interrelationships between these predictors on autistic youths' mathematics achievement. My findings also emphasize the need for teachers to be aware of the variability of mathematical performance among autistic students and implement pedagogical strategies that support their autistic students' G*f*, expressive language, and EF skills.

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Appendix A

Table A

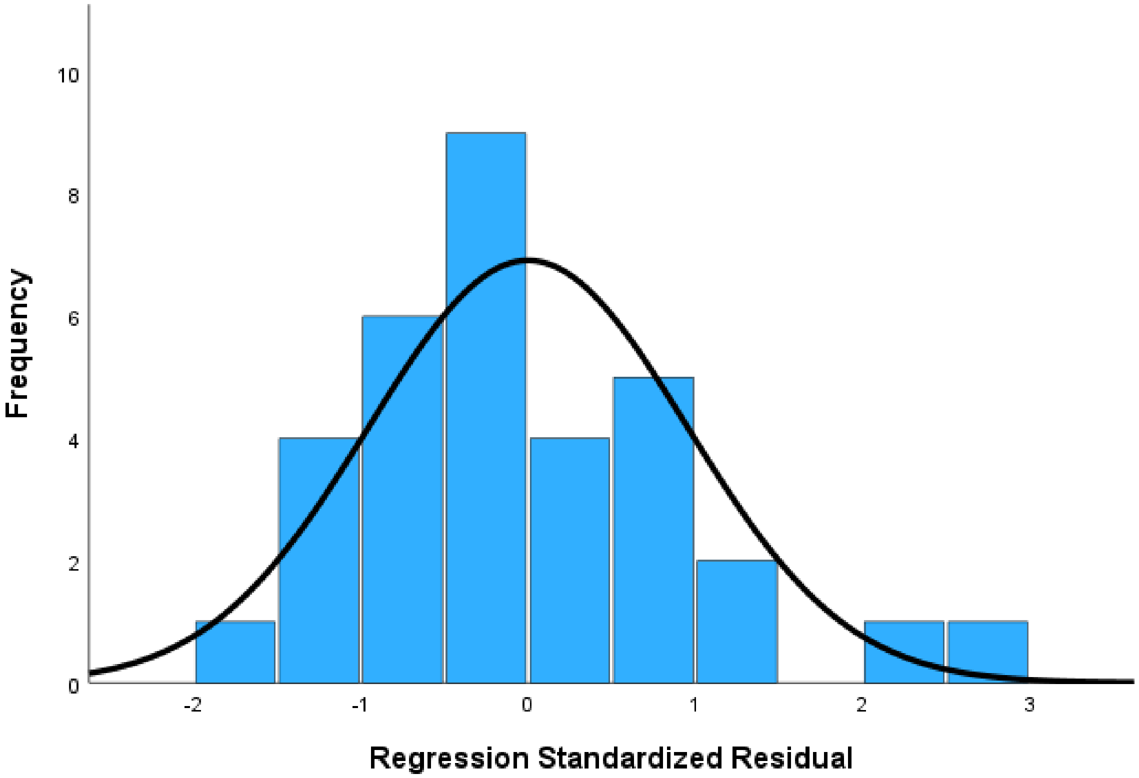
Descriptive Statistics for KeyMath-3 DA^{CDN} Applications

Variable	*N*	*M (SD)*	Range	Kurtosis	Skewness
Age	28	9.64 (3.55)	5-16	-0.58	0.73
Autistic Traits	28	78.14 (9.97)	51-90	2.08	-1.38
Fluid Reasoning	28	105.96 (18.14)	80-145	0.07	0.85
Expressive Language	28	7.96 (2.76)	4-15	0.55	0.89
Executive Functioning	28	71.32 (7.88)	51-83	0.38	-0.72

Appendix B

Figure B1

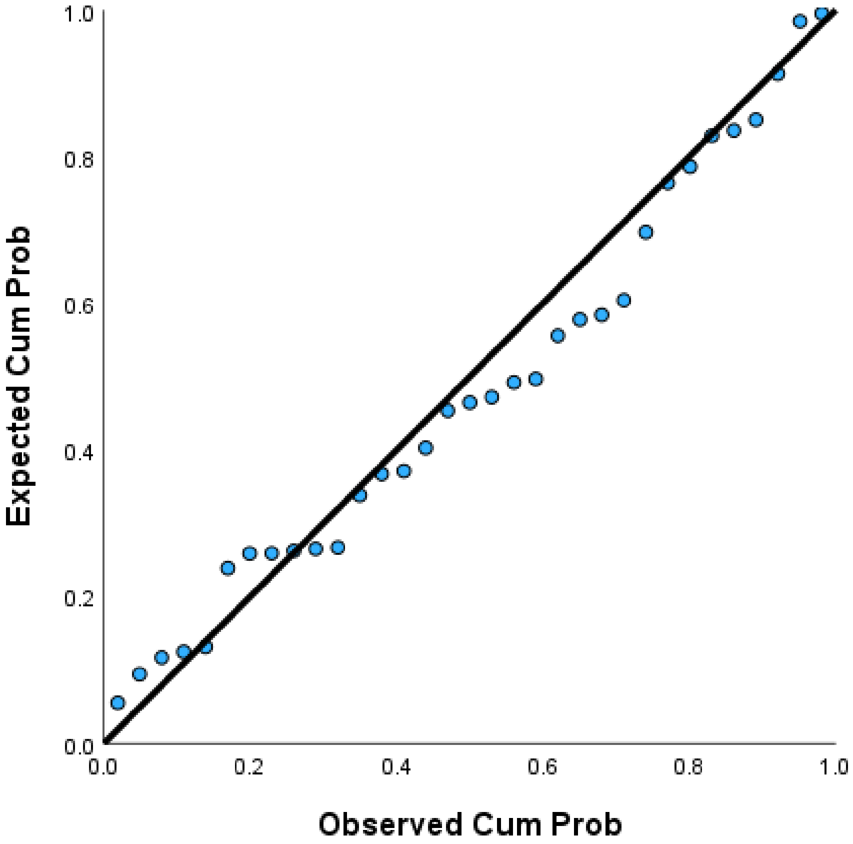
Distribution of Standardized Residuals



Note. The outcome variable is KeyMath-3 DA$^{\text{CDN}}$ Basic Concepts.

Figure B2

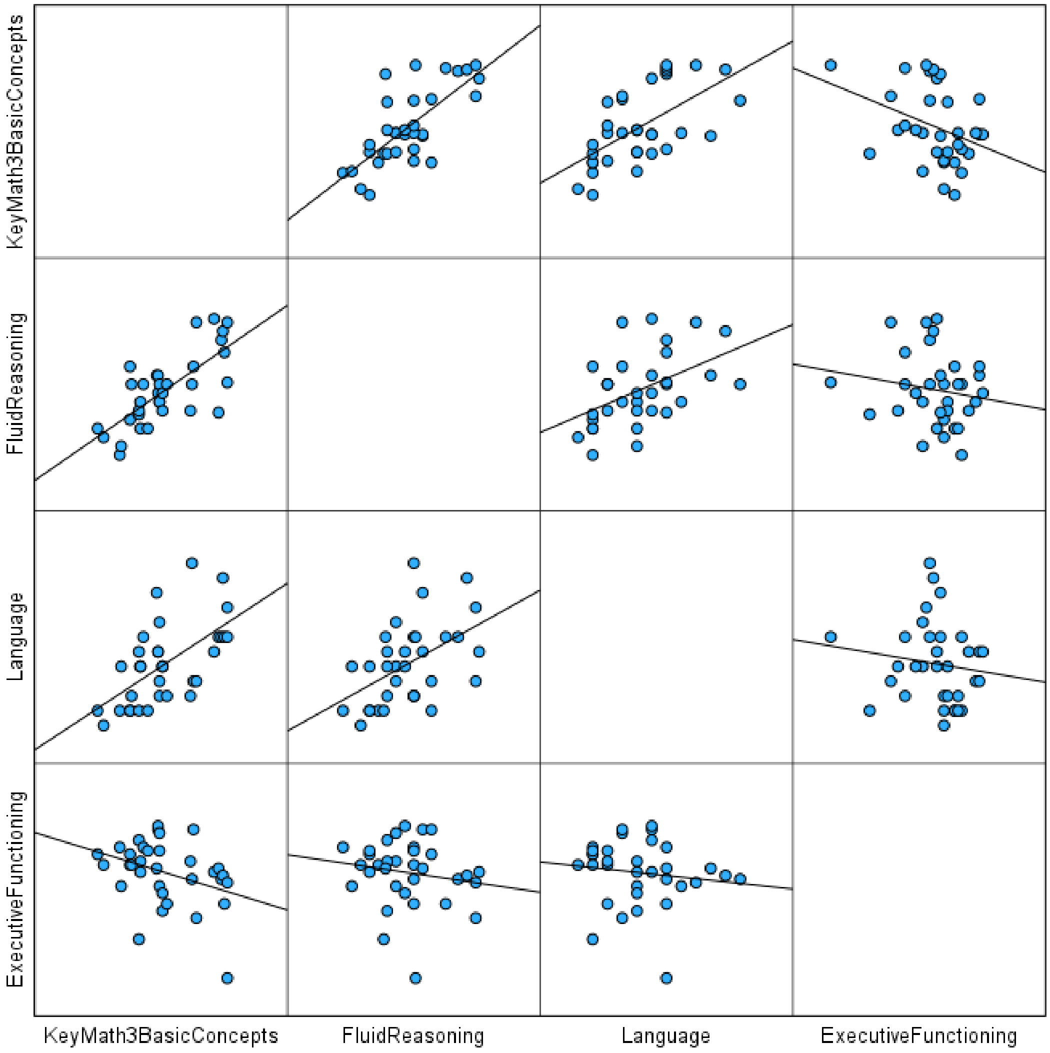
Normal P-P Plot of Standardized Residuals



Note. The outcome variable is KeyMath-3 DA^{CDN} Basic Concepts.

Figure B3

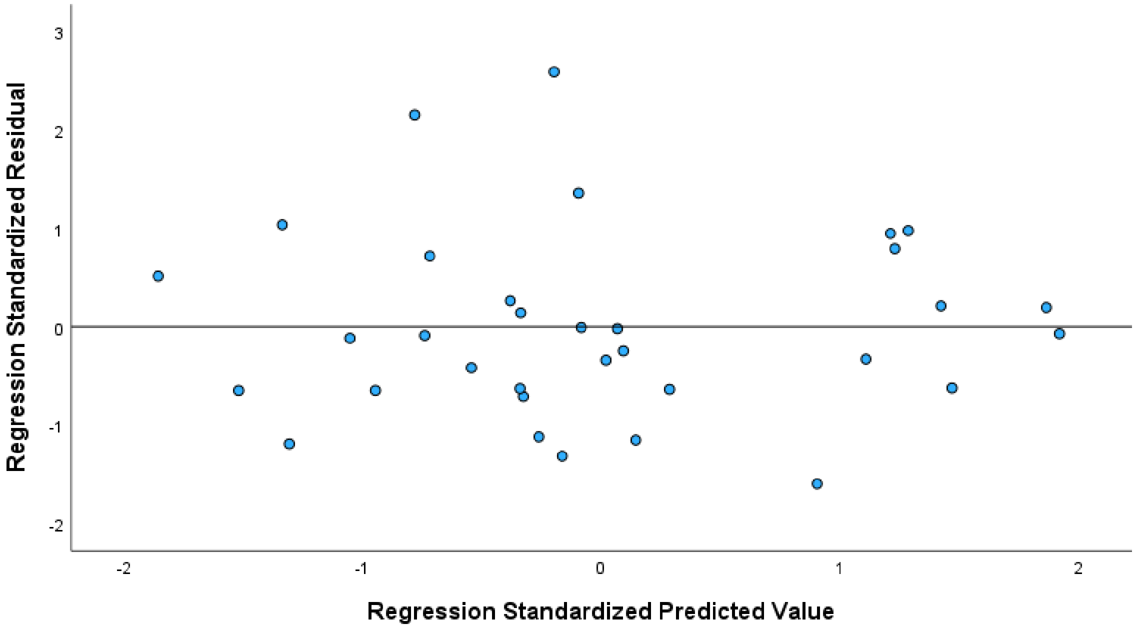
Scatterplot Matrix of Relationships Between Predictor and Outcome Variables



Note. All scatterplots include a fit line.

Figure B4

Scatterplot of Standardized Residuals and Standardized Predicted Values



Note. The outcome variable is KeyMath-3 DA^{CDN} Basic Concepts.