Visuomotor Integration and Literacy Skills in Autistic Children and Adolescents

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Declaration

I, [Pengjie Yang] confirm that the work presented in my thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

Autism spectrum disorder (ASD), henceforth autism, is a neurodevelopmental condition characterized by "persistent deficits in social interaction and communication across multiple contexts," as well as "restricted or repetitive patterns of behaviours, interests, or activities" (DSM-V; American Psychiatric Association, 2013). Autism is a neurodevelopmental condition with ~87% of autistic individuals showing sensorimotor differences (Roman-Urrestarazu et al., 2021). Additionally, these differences are present in several domains, such as physical activities, competence of daily living activities, and school attainment (e.g., literacy skills) in autistic children and adolescents (Miller et al., 2024). Currently, several studies have found that visuomotor integration (i.e., an ability to integrate visual information and motor function; e.g., Beery & Beery, 2014) is positively correlated to literacy skills in non-autistic children and adolescents (Becker et al., 2014; Bellocchi et al., 2017; Cameron et al., 2015), however it remains unclear whether visuomotor integration is related, or indeed, predicts literacy outcomes in autistic children and adolescents.

To fill this research gap and further the understanding of sensorimotor differences and literacy skills in autistic children and adolescents, this PhD programme of work utilised both quantitative and qualitative methods across 4 studies to examine 1) sensorimotor differences in autistic compared to non-autistic populations; 2) whether visuomotor integration, as well as the markers to quantify the underlying motor mechanisms, may predict literacy outcomes in autistic children and adolescents; 3) teachers' beliefs, knowledge and frequency of activities of sensorimotor skills in autistic children and adolescents. In study 1 (Chapter 3), a systematic review was conducted and found that over 50% of the included studies (*n* = 97) showed differences of

sensorimotor control and learning processes in the general autistic population compared to the non-autistic population, using movement outcomes (e.g., movement time and total error) and production measures (e.g., kinematic analysis markers). Few studies have investigated adaption as a function of practice. However, it was shown that blocked practice was an optimal type of practice for sensorimotor learning in autistic populations. In study 2 (Chapter 4), a cross-sectional study investigated 51 verbal autistic children aged 7 to 11 years old on whether visuomotor integration was a predictor of their literacy skills, when accounting for other measures (e.g., intelligence quotient and executive function). The results suggested that full-scale IQ was the only significant predictor of reading. Reading and age were significant predictors of handwriting fluency. Although visuomotor integration was not a significant predictor of literacy skills, it was significantly correlated with reading (r = .53) and handwriting fluency (r =.51). Study 3 (Chapter 5) investigated autistic (n = 32) and nonautistic children (n = 29) aged 7 to 11 years old in two parts. A mixed repeated measure ANOVA found that autistic children had less symbol production error, more symbol production error variability, more variability in percentage time to peak velocity than non-autistic children. Secondly, as an extension of study 2, a cross-sectional study was conducted to investigate whether markers representing the underlying sensorimotor control mechanisms [i.e., sensorimotor planning (e.g., percentage time to peak velocity) and performance (e.g., spatial production error) markers], were predictors of literacy skills in children aged 7 to 11 years old. Similar to the findings of study 2, full-scale IQ was the only significant predictor of reading. Age was a significant predictor of handwriting fluency. Although percentage time to peak velocity and symbol production error were not significant predictors of literacy skills, percentage time to peak velocity was significantly correlated with reading (r = -.26) and handwriting fluency (r =-.35); symbol

production error was significantly correlated with reading (r = .26). In study 4 (Chapter 6), a novel survey was conducted with 114 teaching staff to examine their beliefs, knowledge, and frequency of activities of sensorimotor skills in autistic children aged 7 to 11 years old, compared to other key skills (i.e., literacy and maths skills). It was found that teachers had placed more importance on motor skills, compared to maths skills. Teachers had more variability in knowledge of motor skills, compared to literacy and maths skills. Finally, SEN schoolteachers did more frequent motor skills related activities than mainstream schoolteachers. In Chapter 7, the findings of current studies in this PhD are discussed and appraised. Moreover, implications and limitations of this PhD programme of work are discussed.

Impact Statement

Although sensorimotor control differences and/or difficulties are not classified as the diagnosis criteria in autism (DSM-V; American Psychiatric Association, 2013), recent studies have suggested that sensorimotor control differences are prevalent in approximately 87% of individuals of the autistic population (e.g., Bhat, 2020; Licari et al., 2020; Miller et al., 2021). The sensorimotor control differences are pervasive across all developmental stages (Hannant et al., 2016) and affect various domains, such as social skills, daily living skills and school attainment skills (e.g., literacy skills) (Miller et al., 2024). In early development, literacy skills are recognised as essential components of the National Curriculum in the United Kingdom, and they encompass the skills needed to effectively read, write, speak, and listen (National Literacy Trust, n.d.). These skills enable individuals to communicate and comprehend information proficiently, contributing to their overall academic achievement and success (DfE, 2013).

Visuomotor Integration, the coordination of visual information and motor function, has been positively correlated with literacy skills in early years and school-age children (Cameron et al., 2012, 2016; Khatib et al., 2022; Kim et al., 2018). This relationship suggests that visuomotor integration may underpin domain general processes, including attention, intention and sensorimotor processes, that are also crucial for literacy skills, such as reading and writing (Iacoboni, 2009; Keysers et al., 2018; Schaal et al., 2003). A novelty of the current work is to examine whether sensorimotor control processes, quantified by motor performance and planning markers, predict literacy skills in autistic children in Key Stage 2 (generally aged 7 to 11 years old). Additionally, teachers are regarded as the main stakeholders for children's education in schools

(Sattar et al., 2022), and their beliefs, knowledge, and frequency of activities on sensorimotor motor may impact autistic children's physical education and learning in the school system.

Findings of the PhD programme of work showed that sensorimotor control and learning differences persist in autistic individuals across life span. Also, blocked practice could be the optimal type of practice to enhance sensorimotor learning in autism. Although sensorimotor performance and planning variables were not predictors of literacy skills in autistic children in Key Stage 2, significant positive correlations were found between these variables and literacy outcomes. Furthermore, responses from teachers gathered through a newly designed survey indicate a general lack of knowledge regarding sensorimotor skills. Teachers' beliefs and knowledge were positively correlated. Teachers from special needs schools used motor-related activities more frequently than mainstream schoolteachers. Taken together, the findings provide a foundation for practical guidance for researchers, educators and therapists that investigate sensorimotor interventions for autistic children, informed by the principles of motor control theory.

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Chapter 1: General Introduction and Literature Review

General Introduction

Autism spectrum disorder (ASD), hereafter referred to as autism, is a neurodevelopmental condition characterized by "persistent deficits in social interaction and communication across multiple contexts," as well as "restricted or repetitive patterns of behaviours, interests, or activities" (DSM-V; American Psychiatric Association, 2013). Recently, there has been a significant increase in reported autism cases. The largest and most recent national prevalence study (*n* = 7,047,238) showed a 787% increase in registered diagnoses of autistic children in the UK between 1998 and 2018, resulting in approximately 1 in 57 (1.8%) children being diagnosed (Roman-Urrestarazu et al., 2021). Additionally, Zeidan et al. (2022) reported a global autism prevalence of around 1%, particularly in Western countries, underscoring the importance of investigating autism. With growing recognition of autism, it is essential to explore its diagnosis and prevalence.

While sensorimotor differences are not central to autism diagnosis (as per the DSM-V), research indicates significant differences in sensorimotor control and learning processes between autistic and non-autistic individuals (Cavallo et al., 2021; Fournier et al., 2010; Hayes et al., 2016, 2018; Mari et al., 2003; Rinehart et al., 2001). These differences are evident from an early age, with young autistic children experiencing delays in achieving significant motor milestones (e.g., lying, righting, sitting, and crawling) (Teitelbaum et al., 1998). These motor differences persist into later developmental stages. For example, Kaur et al. (2018) found that autistic children aged 5 to 12 years old exhibited lower gross and fine motor performance, greater movement variability, and weaker interpersonal synchrony, compared to non-autistic

children. Specifically, these sensorimotor differences, including visuomotor integration differences, had an impact on school attainment skills of school aged autistic children (Becker et al., 2014; Carlson et al., 2013).

Literacy skills are crucial in both educational and societal contexts, underpinning several domain-general processes in learning and development (Stuart et al., 2008). The Department of Education (DfE)'s 2013 framework document identified literacy as a key skill in the primary national curriculum, highlighting two main components for Key Stage 2 children: 1) reading (word reading and reading comprehension), and 2) handwriting.

This thesis aims to investigate aspects of sensorimotor control and learning processes in autistic individuals, as well as the relationship between the underlying motor mechanism of visuomotor integration and literacy skills in school age autistic children and adolescents. This PhD programme of work is structured in seven main chapters, framed by an introductory and literature review chapter and a general discussion chapter. The introductory and literature review chapter (Chapter 1) will provide a comprehensive overview of the relevant literature, laying the groundwork for the subsequent studies. The subsequent chapters (chapter 3-6) will synthesise and evaluate findings from each study on different research aims, discussing their theoretical implications for sensorimotor control and autism research and their broader impact. Future research directions will also be proposed. This chapter will review key literature, introduce theories of sensorimotor control and literacy skills and mention about the current research gaps, to offer a clear narrative, outline the context and motivations behind this PhD research programme.

Literature Review

Part 1: Autism

What is Autism?

Autism spectrum disorder (henceforth autism) is a neurodevelopmental disorder characterised by “persistent deficits in social interaction and communication across multiple contexts”, and “restricted or repetitive patterns of behaviours, interests, or activities” (DSM-V; American Psychiatric Association, 2013). Leo Kanner (1943) was the pioneering scientist to identify and describe autism in academic literature, coining the term "an autistic disturbance of affective contact." His groundbreaking paper detailed a case study of eleven children, noting their limited use of communicative language, diminished interest in social interactions, and engagement in repetitive behaviours. Following Kanner, Hans Asperger (1944) published his observations under the title "autistic psychopathy in children," highlighting differences in social interaction, both verbal and non-verbal communication, and restricted, specific interests among the children he studied. The foundational assessments and observations by Kanner (1943) and Asperger (1944) have significantly shaped our current understanding, perception, and diagnostic criteria for autism (American Psychiatric Association, 2013; Harris, 2018). Over the years, global prevalence estimates of autism have increased, a trend attributed to broader diagnostic criteria, the distinction of autism from other developmental disorders, and heightened awareness among both the public and professionals (Baio et al., 2018; Elsabbagh et al., 2012).

History and Diagnosis

Building on the foundational research by Kanner (1943) and Asperger (1944), who first described autism, an epidemiological study on "early infantile autism" conducted by Lotter (1966) found a prevalence rate of approximately 4.5 per 10,000 children. Wing and Gould (1979) further enhanced the understanding of autism by defining the "triad of impairments," which highlighted the three core challenges faced by autistic individuals: social interaction, communication, and imagination. They also categorised autism into three social sub-types: aloof (i.e., socially engaging only when necessary), passive (i.e., willing to interact if others initiate and sustain the social engagement), and odd (i.e., actively engaging in a socially atypical manner). Subsequently, in 1997, Wing further developed this concept by introducing the idea of autism as a spectrum.

Subsequently, in the DSM-IV, the term "Asperger syndrome" was introduced to differentiate individuals with typical intelligence quotient (IQ) and verbal communication skills but who have difficulties with non-verbal communication from those with "autistic disorder" (American Psychiatric Association, 1994). Nonetheless, in 2013, the DSM-V merged all subcategories into a single, inclusive diagnosis known as "autism spectrum disorder," thereby eliminating Asperger syndrome as a separate condition. Currently, the main diagnosis bodies, the Diagnostic and Statistical Manual of Mental Disorders (DSM-V) (American Psychiatric Association, 2013) and the International Classification of Diseases (ICD-11) (World Health Organization, 2019), classify autism as "autism spectrum disorder (ASD)" with two main diagnostic criteria: “persistent *deficits* in social interaction and communication across multiple contexts”, and “r*estricted, repetitive* patterns of behaviour, interests, or activities”.

Part 2. Sensorimotor Processes in Autism

Sensorimotor Differences Across Development

Although sensorimotor differences in autism are not explicitly outlined in diagnostic criteria, these differences have been observed since Leo Kanner's study in 1943, which identified autistic challenges in clumsy gait and gross motor performance (Kanner, 1943). Over the following three decades, research have consistently supported these findings, indicating that sensorimotor differences often manifest early in the development of autism, sometimes appearing before core features such as social interaction (Teitelbaum et al., 1998; LeBarton & Landa, 2019).

Sensorimotor differences in autism can be observed in infancy (Brian et al., 2008; Provost et al., 2017). For example, Brian et al. (2008) found that 18-month-old infants with high-risk in autism have atypical sensorimotor behaviours (e.g., hands and arms mannerisms: “arm waved” and “hands to ear” more frequently) in sensorimotor domain items of standard assessments (e.g., Autism Observation Scale for Infants, Bryson et al., 2008). They also suggested that the atypical sensorimotor behaviours observed in autism in high-risk at 18 months of age are highly predictive of autism diagnosis at 3 years of age in toddlers at risk. Sensorimotor differences are also apparent in childhood (i.e., gross sensorimotor milestones delays – walking independently delays, walking steps delays) and adulthood (i.e., slower reaction time when walking across the road) (Fournier et al., 2010). Sensorimotor processes have also been shown to relate to everyday abilities, such as language development (Gernsbacher et al., 2008), playing and interacting with others (Clearfield, 2011) and perception (Wilson & Knoblich, 2005), which may have a positive impact on the

development of daily life skills (e.g., walking on the stairs independently in early years and clear expression with verbal language) (Jasmin et al., 2009) Thus, It is important to understand the underlying sensorimotor processes of autism, in order to increase the life quality (Jasmin et al., 2009) and potential development in language (Stone et al., 2000), cognitive (Caron et al., 2006) and social aspects (Wolpert et al., 2003).

Sensorimotor Skills

Autistic individuals demonstrate sensorimotor skills difficulties (e.g., poorer object control skills - more difficulties to eat with a spoon) during everyday life (Green et al., 2009). These difficulties influence the development of fundamental movement skills (e.g., locomotion; object control; stability), which are important for physical and social development, and well-being (Nemeth et al., 2010; Vivanti et al., 2018). Some sensorimotor skills (e.g., informational gestures = a high-five) are a means of social communication and interaction, and therefore may have an impact on quality of life and functional social development (Cook, 2016; Nebel et al., 2016). Therefore, a key focus of current autism research is to examine whether there is a connection between sensorimotor development and the acquisition of social skills that underpin very important aspects of social interaction/learning (e.g., imitation; action understanding) (Krishnan-Barman et al., 2017; Li et al., 2017).

Sensorimotor processing differences in autism also impact the acquisition of novel sensorimotor skills (e.g., riding a bike) during physical practice and/or training (Hannant et al., 2016). According to Mostofsky et al. (2006), the neural mechanisms underlie differences in sensorimotor coordination/execution may influence sensorimotor skill learning.

Sensorimotor Control

Based on Wolpert and Flanagan (2001), sensorimotor control is a process involving the conversion of sensory inputs into motor outputs, regulated by the central nervous system (CNS) to execute voluntary movements, such as grasping a cup. As illustrated in Figure 1, the computational framework of sensorimotor control processes by Gowen and Hamilton (2013) can explain the underlying sensorimotor processes, and the mechanisms recruited, engaged, resulting in and during sensorimotor execution throughout an action. The following subsections will elaborate sensorimotor processes through an action (i.e., grasping a cup) in 5 stages: 1) sensory systems; 2) state estimation; 3) sensorimotor planning; 4) feedforward model; 5) sensorimotor execution, as well as the implication of these stages in autistic sensorimotor control. Notably, it's crucial to note that these stages are interconnected and not completely distinct despite they are outlined in a step-by-step fashion. Individuals may have to consistently manipulate and integrate sensory inputs from different channels, such as using vision and proprioception resources to adjust ongoing movements in response to changing situations or new information of the proposed action.

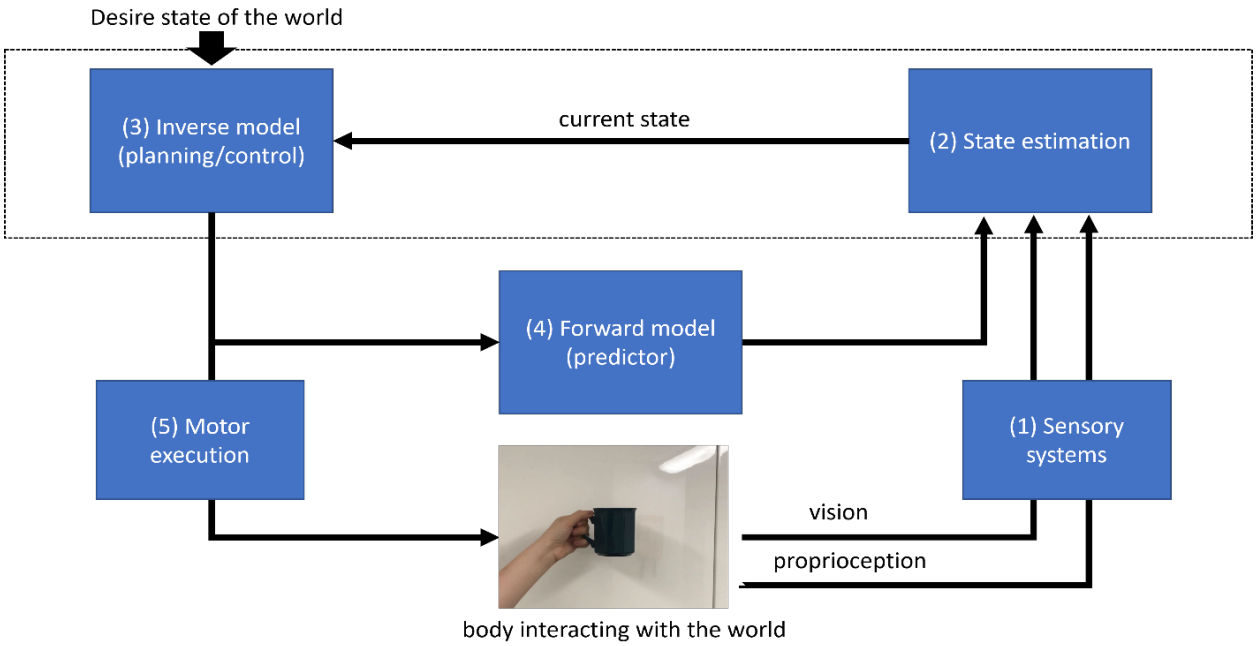

Figure 1- Illustration of different computational processes involved in sensorimotor control, adapted from Gowen and Hamilton (2013)

Sensory Systems

As illustrated in Figure 1, the computational framework of sensorimotor control processes by Gowen and Hamilton (2013) suggested that accurate sensory inputs such as vision and proprioception, are essential to gather useful information to inform feedforward predictions and create a precise movement. To form a precise goal-directed movement, the brain first receives the raw sensory input signals from eyes, skin and joint receptors without error. Then, the signals must be interpreted by the brain. For example, a goal-directed movement, such as holding a cup by hand, will firstly create a visual image in the brain and then the signals will transform the image into an estimation of the hand and cup location.

In terms of autism in sensory differences, Glazebrook et al. (2009) provided indirect evidence of intact proprioception of autistic, compared to non-autistic

individuals. Participants were asked to perform a pointing task while the vision of their hands or visual environment was either available or removed. Without visual feedback, the accuracy of autistic and non-autistic individuals was similar. Whereas with visual feedback, autistic individuals took longer movement duration and overshoots the target than non-autistic individuals. The result suggested during movements the proprioceptive signals were operational in controlling the movement, but the processing and integration of visual feedback to guide the movement was less effective for autistic individuals. Other findings also suggested that autism had lower accuracy and more variability in detecting biological and coherent motions (Cook et al., 2009; Milne et al., 2019; Pellicano & Gibson, 2008) than non-autistic individuals, indicating potential challenges in autism to integrating visual sensory inputs. The differences on sensory systems could lead to sensorimotor differences in autism. This may have an impact on sensorimotor planning and predicting the movements (Rinehart et al., 2006a), which will be discussed in following sections.

State Estimation

After receiving and interpreting the sensory signals, the brain requires a state estimate of the body and the work in the current environment, to create and update sensorimotor plans (Gowen & Hamiliton, 2013). Collected information will be integrated to form an estimate of an individual's present condition. For example, the task is to put a spoon in a cup a performer is required to process (estimate) the location of the cup in space in relation to the location of the spoon in your hand. To do this, visual information is essential for target location (cup), including its size and shape, whether there are any obstacles or any other relevant information (e.g., weight or direction of the target). Meanwhile, the integration of visual and proprioception information will determine the hand location and the grip of the spoon. The

sensorimotor system's sensory components engage in multisensory processing (hence MSI), integrating visual and proprioceptive inputs to refine state estimation accuracy (Gowen & Hamilton, 2013; Molinari & Masciullo, 2019).

In terms of autism studies (e.g.,Van der Smagt et al., 2007; Williams et al., 2004b), few empirical studies have investigated the integration of different sensory signals in autism. Several studies on visual and auditory stimuli suggested a mixed results. Williams et al. (2004b) found that autistic individuals had similar movement time with non-autistic individuals, using the integration of visual and auditory stimuli. More recent studies have shown that autism was less consistent and took more time to integrate visual and auditory stimuli (Kwakye et al., 2011, Taylor et al., 2013). The differences of integration of two or more sensory signals may contribute to a slower and more variable sensorimotor control processes.

Sensorimotor Planning

Sensorimotor planning involves translating the generated state estimation and desired movement goal into the appropriate series of sensorimotor commands, relative to one's current state, to execute a specific movement, such as reaching for a cup (Gowen & Hamilton, 2013). When aiming to reach and grasp a coffee cup, the individual relies on the formulated state estimation (e.g., an overview of the environment and their position within it) to determine the force production and motor action pattern necessary to direct the hand towards the handle of the cup (Wolpert, 1997). Motor planning involves evaluating the cost of movements to select the optimal action. The specific forces and sequences needed to swiftly and controlled move the limb, while ensuring a comfortable posture at the target location (e.g., holding a cup), are determined by recalling similar past actions from the sensorimotor repertoire

(Rosenbaum et al., 1992). For instance, using the right hand to pick up the cup on the right side of the body is more efficient than using the left hand. Motor planning extends beyond the initial stage before movement begins; it is an ongoing process that can be refined and updated in real-time to correct emerging errors and adapt the trajectory of the movement as it progresses.

In recent studies on sensorimotor planning in autism, reaction time is a key metric for examining sensorimotor planning processes (Glazebrook et al., 2006, 2008, 2009; Nazarali et al., 2009; Rinehart et al., 2001, 2006a). Research indicates that autistic individuals typically have slower reaction times for goal-directed movements compared to non-autistic individuals. For instance, a study by Glazebrook et al. (2006) required participants to reach a target circle quickly and accurately with their index finger upon seeing a visual cue. The findings showed that autistic children had slower reaction times than non-autistic children. The study also examined kinematic markers like peak acceleration, time to peak acceleration, peak velocity, and time to peak velocity, revealing that autistic individuals exhibited lower peak acceleration and velocity, longer times to peak velocity, and more variability in peak acceleration displacement. Kinematic analyses of upper limb sensorimotor control tasks have shown that autistic individuals experience greater temporal and spatial variability during the initial movement phase (Forti et al., 2011; Foster et al., 2020a; Glazebrook et al., 2006; Hayes et al., 2016), which may be due to difficulties in accurately specifying the necessary forces for movement execution while forming a motor plan (Wolpert et al., 1995). Additionally, force production studies highlight sensorimotor planning differences between autistic and non-autistic individuals. David et al. (2009) investigated a precision grip task, assessing variables such as peak grip force, grip-

to-load force onset latency, grip force at load force onset, and time to peak grip force. The results showed that autistic children had longer grip-to-load force onset latency and greater grip force at load force onset, indicating autism-specific differences in sensorimotor planning related to precise muscle force specification (Mosconi et al., 2015; Wang et al., 2015; Wolpert et al., 1995). A motor plan lacking precise or accurate force specifications can lead to increased variability during execution, necessitating more frequent online adjustments and error corrections.

Feedforward Sensorimotor Control

The generation of a sensorimotor command involves specifying the execution profile of a movement and creating an efference copy, which serves as an internal forward model for the upcoming action, predicting the expected sensory consequences (Wolpert et al., 1995; Wolpert & Flanagan, 2001). Studies have shown differences in sensorimotor control processes between autistic and non-autistic individuals, such as longer reaction times and greater grip force in autism (David et al., 2009; Foster et al., 2020; Glazebrook et al., 2008). Comparing the efference copy with actual sensory feedback allows adjustments to muscular forces crucial for reaching a target, enabling adaptation of acceleration and deceleration profiles (Elliott et al., 2010). This form of sensorimotor control occurs early in movement execution, allowing examination of underlying kinematic properties (Elliott et al., 2010).

During manual aiming movements, autistic participants exhibited greater spatial variability at peak acceleration compared to non-autistic participants (Glazebrook et al., 2006). This variability decreases by the time of peak velocity, suggesting that initial movement differences are likely related to feedforward control, which is subsequently

supplemented by online control using available sensory feedback as the movement progresses (e.g., vision or proprioception).

Sensorimotor Execution

Once movement goals have been translated into sensorimotor commands, these commands are transmitted to the relevant muscle groups to initiate and execute the desired movement. Studies reported atypical movement execution in autistic individuals compared to non-autistic individuals (Cook et al., 2013; Rinehart et al., 2006a). During reach-to-grasp movements, autistic individuals have been observed to exhibit longer movement durations and decelerations, lower amplitudes of peak velocity, and delayed maximum grip aperture than non-autistic individuals (Mari et al., 2003). Additionally, the underlying kinematics of sinusoidal arm movements in autistic adults show differing patterns, characterized by greater velocity, acceleration, and jerk (Cook et al., 2013). Moreover, autistic adults demonstrated increased spatial variability of peak acceleration in goal-directed movements than non-autistic adults (Glazebrook et al., 2006). This growing body of evidence indicates clear differences in the underlying kinematic profiles of autistic individuals.

Theoretical Framework for Sensorimotor Control: The Multiple-Process Model of Limb Control

Woodworth (1899) introduced a theoretical model to explain the precision and regulation of voluntary movement, particularly goal-directed aiming movements, such as grasping a cup or shooting a ball into a basket. According to Woodworth, these movements consist of two phases: 1) a ballistic phase where the limb moves towards the target, followed by 2) a corrective phase where feedback mechanisms, such as

visual and proprioceptive cues, are utilized to minimize the discrepancy between the limb and the target position. While Woodworth's dual-component model has been widely used, subsequent researchers (Beggs & Howarth, 1972; Crossman & Goodeve, 1983; Keele, 1968) introduced various adaptations to explore the relationship between movement speed and accuracy in goal-directed aiming movements (Fitts, 1954; Fitts & Peterson, 1964). Despite the significance of sensorimotor planning and online control in determining the speed and precision of goal-directed aiming movements, it's evident that Woodworth's simplistic two-component model and its iterations are unable to fully explain the adaptability and complexity of skilled upper limb motor control in such movements (Elliott et al., 2010). Consequently, Elliott et al. (2010) proposed a novel model of upper limb motor control for goal-directed movements termed the "Multiple-Process Model of Limb Control."

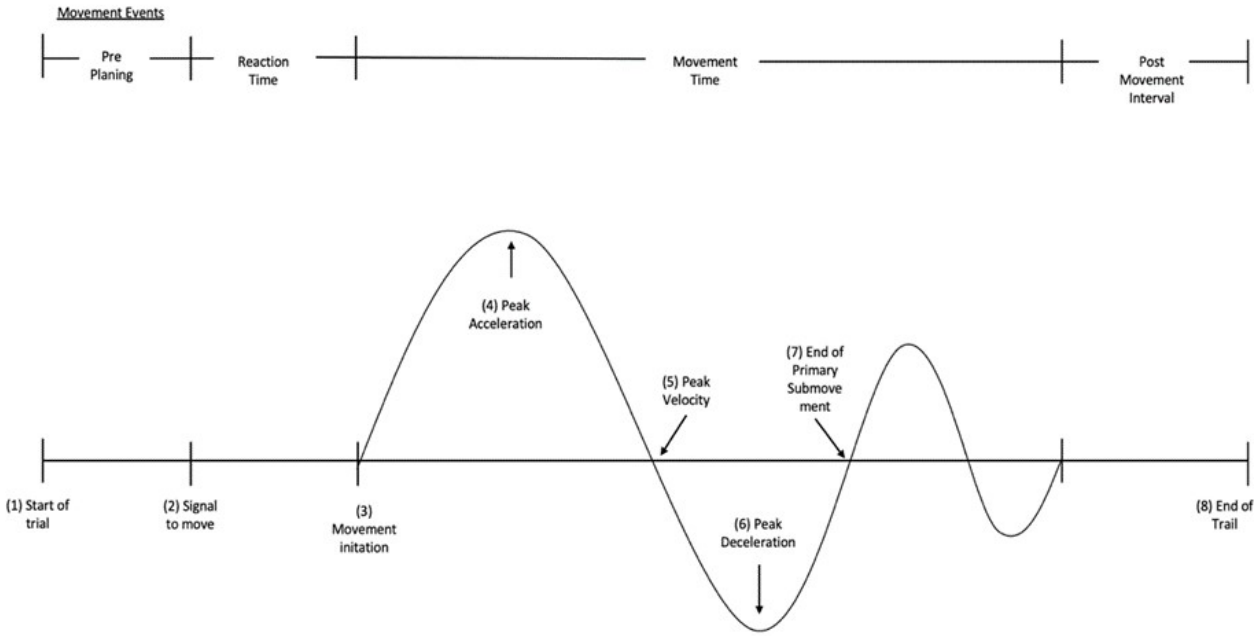

Figure 2: Illustration of specific acceleration profile that include multiple processing events linked to a single goal-directed movement towards a small target (adapted from Elliot et al.,2010)

As illustrated in Figure 2, “pre-planning” stage represents the time between the start of a trial and the signal to move. During this stage, individuals received advanced information from vision and proprioception (e.g., the location of the target and object, instruction to move the object to the target, estimate the weight and speed that may optimize the movement), a motor plan is generated. Initial feedback facilitates corrections to early movement impulses, while ongoing impulse control entails making incremental adjustments based on anticipated sensory outcomes (Saunders & Knill, 2003). The “pre-planning” stage is followed by the “reaction time”, that is the time between signal to move and movement initiation. In the context of sensorimotor planning, reaction time is a key measure of sensorimotor planning processes (Anderson et al., 2001). It encompasses the interval between the cue to move and the onset of movement and involves specifying the timing of muscular forces and forming internal representations of anticipated motor outputs and sensory consequences. Prolonged reaction time can lead to slower motor execution, highlighting reaction time as a critical metric in the motor planning phase (Gowen & Hamilton, 2013).

The “movement phase” lasts from the initiation of the movement to the end of the movement. In Figure 2, different kinematic markers (i.e., peak acceleration, peak velocity and peak deceleration) represent and demonstrated specific movement phases. In terms of peak acceleration, it represents the maximum change in velocity during a movement, reaching its highest point at a specific stage in the motion. Its

purpose is to compare the anticipated result with the actual result and regulate impulses. In terms of peak velocity, it represents the highest rate of motion achieved during the performance of a specific action. In terms of peak deceleration, it refers to the most notable reduction in speed experienced during the execution of a defined movement and reflects a negative change in velocity. These kinematic markers are integral to both feedforward and feedback processes in sensorimotor control. The feedforward mechanism initiates adjustments by comparing motor commands with anticipated outcomes using an efference copy linked with early kinematic markers (pre-peak velocity). Conversely, the feedback process involves rectifying the movement by comparing the intended state with the current state, associated with later kinematic parameters (post-peak velocity) (Elliott et al., 2010; Meyer et al., 1982). Heightened variability in peak acceleration, deceleration, or velocity signifies less efficient motor control, potentially attributable to difficulties in motor planning and accurately specifying forces for movement execution within an internal action model (Foster et al., 2020; Wolpert et al., 1995).

The multiple-process model of goal-directed aiming suggests that performers adapt their primary movement endpoints across trials to enhance endpoint variability (Worringham, 1991). In contrast to the optimised submovement model (Meyer et al., 1988), which prioritizes endpoint refinement, this model considers the trade-offs between undershooting and overshooting. Typically, undershooting is favoured due to its lower costs compared to overshooting, which entails greater distance and the need to reverse from zero velocity (Meyer et al., 1982). Various factors, such as effector mass and corrective movements against gravity, can influence the degree of undershooting (Lyons et al., 2006). Although overshooting may occur in scenarios

where less force leads to greater distance, energy conservation remains paramount (Oliveira et al., 2005).

Practice plays a significant role in shaping both the central tendency and variability of movement endpoints. Moderate practice helps establish a consistent distribution of endpoints that optimizes speed, accuracy, and energy expenditure (Elliott et al., 2009). Corrections prompted by neural-motor noise are often guided by visual feedback acquired late in the primary submovement (Starkes et al., 2002). With continued practice, these corrective submovements become quicker and more effective (Pratt & Abrams, 1994), contributing to improved precision in force specification and impulse control (Khan et al., 1998).

To summarise, the multiple-process model encompasses three forms of online regulation: early efferent control, early and continuous afferent control, and late visual control. These processes refine internal models over successive trials, minimizing disparities between anticipated and actual outcomes. Through practice, the motor system fine-tunes force-time parameters, enhancing both primary and corrective movements (Meyer et al., 1988). This model underscores the importance of integrating advanced information, ongoing feedback, and practice to optimize motor performance in terms of speed, accuracy, and energy efficiency.

Sensorimotor Learning

When acquiring a new movement skill, individuals develop an internal action model by linking sensory feedback (such as proprioception and vision) with sensorimotor commands (Haswell et al., 2009). These internal action models serve as

the foundation for controlling goal-directed behaviours, facilitating further learning and decision-making in complex environments (Centelles et al., 2013; Hamilton, 2013). They aid in sensorimotor control by comparing expected sensory outcomes with actual sensory input (Wolpert et al., 1995). While autistic individuals are capable of forming internal action models (Gidley Larson et al., 2008; Hayes et al., 2017), they may rely more heavily on proprioceptive feedback and less on visual feedback compared to non-autistic individuals (Haswell et al., 2009; Izawa et al., 2012; Mostofsky & Ewen, 2011). This increased reliance on proprioception may contribute to difficulties in imitation performance and social interaction among autistic individuals (Haswell et al., 2009).

Imitation

Imitation plays a vital role in learning new sensorimotor behaviours and contributes to the development of social cognition (Hayes et al., 2017; Rogers et al., 2010). It involves observing and replicating movements demonstrated by others, such as reaching for and grasping an object (Heyes, 2001). Autistic individuals often encounter difficulties in imitation compared to typically developing individuals (Rogers & Pennington, 1991; Vivanti & Hamilton, 2014). These challenges include struggles in imitating actions and representing observed biological motion (Hamilton, 2013; Stewart et al., 2013).

Analysing imitation performance across different stages, particularly early and late stages, can provide valuable insights into adaptation processes during observation learning (Bird & Heyes, 2005; Byrne & Russon, 1998; Hayes et al., 2010). Studies have shown successful sensorimotor adaptation in autism, such as comparable rates of adaptation in hand displacement during tasks like catching balls

of varying weights (Mostofsky et al., 2004). This adaptation is believed to involve cerebellar processes (Fuentes et al., 2009; Gidley Larson et al., 2008; Mostofsky et al., 2006). Additionally, providing autistic individuals with repetitive task goals in predictable trial blocks has facilitated imitation of both typical and atypical biological motion kinematics (Foster et al., 2020a; Hayes et al., 2016).

Recent research focus on understanding the underlying sensorimotor mechanisms in autism, particularly differences in sensorimotor skills (Foster et al., 2020a; Hayes et al., 2018). Standardised assessments, such as the Movement Assessment Battery for Children (MABC-2) and Peabody Developmental Sensorimotor Scales (PDMS-2), highlighted differences in fine and gross sensorimotor skills between autistic and non-autistic individuals (Green et al., 2002; Minshew et al., 2004). However, the specific underlying sensorimotor processes that are unique to autism, such as sensorimotor planning differences, remain unclear (Foster et al., 2020; Hayes et al., 2018). Understanding these specific computational sensorimotor mechanisms is crucial for elucidating differences in autism (Gowen & Hamilton, 2013).

During action execution, sensorimotor commands are generated based on sensory information to optimise performance through prediction and reaction (Wolpert et al., 2011). These commands are informed by internal action models, which integrate sensory and sensorimotor information (Elliot et al., 2010). Further exploration of internal action models in autism will be discussed in the literature review section of this report, aiming to provide insights into differences in sensorimotor computation stages in autism.

Part 3. Sensorimotor and Literacy skills in Autism

Part 3 will discuss these parts: literacy skills in autism, literacy skills in key stage 2, sensorimotor and literacy skills in autism.

Literacy Skills in Autism

Based on the National Literacy Trust (n.d.), literacy is defined as “the ability to read, write, speak, and listen in a way that lets us communicate effectively and make sense of the world”. Literacy skills play a vital role in children's learning and growth, involving reading and writing and relying on both spoken language and cognitive processes essential for using written language effectively (Kim et al., 2013). For instance, writing facilitates the recording, accumulation, and preservation of knowledge in a readily accessible format (Bormuth, 1973). Moreover, written, and oral language enables communication across various domains, including politics, literature, and social issues. The significance of well-developed literacy skills is evident in their emphasis within educational systems and society, as they serve as the foundation for academic achievement and continuous learning, benefiting individuals in school and everyday life (Koenig et al., 1994).

In 2016, approximately 2.5 million adults lacked functional literacy, suggesting an inability to read or write proficiently (National Literacy Trust (n.d.). Schleicher (2019) predicted an increase to 3.5 million low-literate individuals by 2024. Low-literacy individuals encounter various daily challenges, such as difficulties in understanding healthcare terminology and accessing services, as well as limitations in workforce participation and educational attainment (Baker, 1996; Seidenberg, 2013; Weiss et al.,

1992). Notably, research indicates that autistic individuals often struggle with reading and writing (Grace et al., 2018; Rosenblum et al., 2016; Solari et al., 2019). Solari et al. (2019) examined reading proficiency in verbally proficient autistic children matched for cognitive ability with non-autistic peers. They found that only 31.2% of autistic children achieved average reading scores, contrasting with the 80% average score achievement among non-autistic children. This suggests that autistic children may not effectively respond to conventional reading instruction methods. Additionally, a study by Beversdorf et al. (2001) used a free writing task and found that autistic adults showed larger handwriting compared to non-autistic adults of similar age and IQ levels. This difference remains when their education levels were accounted for suggesting that the handwriting size differences (with a larger writing amplitude) could be linked to motor coordination challenges in autistic individuals. For example, in the Beversdorf et al. (2001) study, which is a free writing task that did not provide autistic adults with instructions on how to perform the letter writing, the greater amplitude in letter writing might therefore be related to motor planning problems associated with the specification and timing of forces that underpin hand and pencil control (Elliott et al., 2010). A potential neural mechanism for motor control problems in autism is the cerebellum (Mostofsky et al., 2009). While Beversdorf et al. (2001)'s study did not assess handwriting precision (e.g., tracing tasks), the results imply that motor coordination difficulties may contribute to atypical handwriting patterns in autism. This finding emphasises the need to consider motor coordination in literacy support for autistic individuals.

Literacy Skills in Key Stage 2

Recognising the pivotal role of literacy in various facets of everyday life, including healthcare, employment, and education, the Department for Education (DfE, 2013) emphasized its paramount importance within the UK national curriculum and society at large. Nevertheless, according to the *Special Educational Needs and Disability: An Analysis and Summary of Data Sources* report (DfE, 2024), only 24% of pupils with special educational needs (SEN), including autistic pupils, met the expected standards in reading, writing, and mathematics by the end of Key Stage 2 in 2022 to 2023, compared to 70% of their peers without SEN. Also, SEN pupils have lower progress scores compared to their non-SEN peers, where progress scores measure a pupil's improvement relative to others nationally with similar prior attainment. A score of 0 reflects average progress, with scores below 0 indicating less progress and scores above 0 indicating more. In 2022–2023, SEN pupils had progress scores of -0.58 in reading, -0.84 in mathematics, and -1.53 in writing, while non-SEN pupils scored 0.42 in reading, 0.45 in mathematics, and 0.62 in writing. The particularly low score of -1.53 in teacher-assessed writing among SEN pupils' highlighted writing as an area of need for targeted academic support, especially in literacy, as well as other subjects, during Key Stage 2.

Key Stage 2, targeting children between the ages of 7 and 11, serves as a crucial period in the development of literacy skills. While the early years and Key Stage 1 lay the groundwork, focusing on aspects like spelling and phonics, it is during Key Stage 2 that students must deepen their understanding and proficiency in reading and writing, preparing them for the rigors of secondary education.

The Department for Education's (DfE) framework document of 2013 highlighted the vital role of literacy skills in children's holistic development, encompassing cultural, emotional, intellectual, social, and spiritual dimensions. Within this framework, reading proficiency in Key Stages 2 is delineated into two main aspects: word reading and reading comprehension. Word reading involves the application of core cognitive processes such as attention and memory to decode both unfamiliar and familiar printed words, requiring not only visual recognition but also the association of printed symbols with spoken sounds (Storch & Whitehurst, 2002). In terms of reading comprehension, previous studies have emphasised the importance of linguistic competence and general knowledge. To comprehend a sentence or paragraph, children must continuously integrate what they've previously read with their own background knowledge to form a continuous mental model of the text (Graesser et al., 1994). At the same time, they need to carefully monitor their understanding and address any areas of confusion or misunderstanding (Denton et al., 2017). Children are encouraged to engage in diverse reading materials to expand their understanding of themselves, the world around them, and to foster creativity and imagination.

The primary national curriculum places significant importance on writing skills, particularly in two domains: transcription (spelling and handwriting) and composition (articulating and structuring ideas in writing). Transcription proficiency, essential for smooth writing, relies on various factors such as accurate spelling achieved through phonetic awareness, word structure, and spelling conventions. Composition skills involve the ability to generate, articulate, and convey ideas through written expression. Assessing the fluency and legibility of handwriting serves as a measure of children's transcription competence.

This PhD investigates autistic children aged 7 to 11 years old (Key Stage 2). Three literacy facets were chosen aligning with the requisites outlined in the national curriculum for Key Stage 2 students: 1) single word reading accuracy; 2) reading comprehension at a paragraph level; 3) handwriting fluency.

Theoretical Framework for Word Reading and Reading Comprehension: The Simple View of Reading

The Simple View of Reading (SVR) suggests that learning to read involves two interdependent processes: decode words and language comprehension (Hoover & Gough, 1990; Stuart et al.,2008). An equation *'RC = LC × D'* was proposed in (Gough & Tunmer, 1986). *D*, represents word reading, particularly refers to single word decoding, characterised as the ability to 'read isolated words quickly, accurately, silently' (Gough & Tunmer, 1986, p. 7). Accurate decoding requires phonological awareness and orthographic knowledge (Hoover & Gough, 1990) that is the reader requires to have the ability to recognise the word by understanding grapheme phoneme correspondence rules (e.g., the relationship between letters and their sounds and spelling patterns). *LC,* represents language comprehension, defined as the ability to "understand language" (Hoover & Gough, 1990, p. 131) or "the process by which, given lexical (i.e., word) information, sentences and discourses are interpreted" (Gough & Tunmer, 1990, p. 7). Effective language comprehension relies on oral language skills such as semantic and syntactic awareness (Hoover & Gough, 1990, p. 131). In this equation, SVR indicated that reading comprehension is the product, rather than the *sum* of decoding and comprehension. Effective reading relies on both decoding and language comprehension skills operating together. Without

either of these components, such as in pre-readers or when proficient readers encounter unfamiliar words, full reading comprehension cannot occur (Gough et al., 1996). Thus, the Simple View of Reading highlights the necessity of both language comprehension (LC) and decoding (D) for comprehension, underlining that while each component is significant, they are insufficient when considered individually.

SVR also emphasised that the connections between decoding and reading comprehension, as well as language comprehension and reading comprehension, are not static but rather evolve throughout reading development. Previous studies suggested that children's decoding abilities serve as strong predictors of reading performance in early age. When they are at older age (e.g., aged 11-13 years old, Vellutino et al., 2007), as they acquire more complex literacy skills, the predictive role of language comprehension becomes increasingly crucial, enhancing fluency and accuracy in reading. This evolving predictive capacity of decoding is attributed to the reduced performance gaps on decoding tasks as children progress, which makes it increasingly challenging to gauge comprehension. Additionally, decoding, primarily rooted in lower-level processes like phonological awareness, may seem more manageable compared to language comprehension, which involves higher-level processes such as grammar and vocabulary (Vellutino et al., 2007). As students encounter more intricate texts in later schooling, the demands on language comprehension intensify, necessitating them to decipher unfamiliar words, establish connections with their meanings, and grasp the structure of sentences or paragraphs.

In terms of the use of SVR in education, this framework is used widely in schools (DFE, 2021) and is the model of choice for reading components for this PhD. A

longitudinal study by LARR (i.e., Language and Reading Research Consortium) and Chiu (2018) investigated 420 children from tracked from early year to Grade three (aged from 5 to 9 years old) showed that 94% of the variance reading comprehension could be explained by the two components of the SVR. in Grade Three (age eight to nine years). Decoded-related skills were found as a predictor for children's later comprehension. Additionally, a study by Lonigan et al. (2018) investigated 757 children from Grade 3-5 (aged 7 to 10 years old) showed that 85% of the variance in reading comprehension was explained by decoding and language comprehension. Therefore, it is important to investigate both the decoding skill (i.e., word reading) and comprehension skill in children aged 7 to 11 years old in this thesis.

Handwriting Difficulties in Autism

In current literature, autistic individuals exhibit handwriting difficulties throughout their lives (Johnson et al., 2013; Myles et al., 2003; Rosenblum et al., 2016). These motor tasks are more difficult in autism compared to non-autistic individuals, as the tasks involve the integration of visual and motor information (Grace et al., 2018). A study by Johnson et al. (2013) investigated handwriting size by having autistic and non-autistic children aged 8 to 13 repeatedly write the cursive letter "l" on a graphic tablet. The results indicated that autistic children produced significantly larger letters and showed more variability in their handwriting compared to non-autistic children. Writing in large or disproportionately sized letters can significantly impact handwriting legibility and efficiency, as it may occupy more space on pre-lined paper and require additional time to complete writing tasks. This suggests that children may need more fine motor effort, leading to quicker fatigue, especially during tasks that involve writing longer paragraphs. Furthermore, variability in handwriting, characterised by inconsistencies in

letter size, formation, spacing, and line adherence, can further decrease legibility and slow writing speed. These factors may lead to challenges for children in completing written assignments effectively and efficiently.

Similarly, Grace et al. (2018) studied autistic and non-autistic children aged 8 to 12, asking them to write four letters sequentially in five different conditions (1. eeee, 2. eeel, 3. eeeem, 4. elel, 5. emem) on a graphic tablet. The autistic children demonstrated greater variability in their handwriting than their non-autistic counterparts, suggesting atypical sensorimotor planning and execution in autistic individuals.

Beyond handwriting quality, handwriting fluency (i.e., speed) is also crucial. Current literature highlights differences in handwriting fluency between autistic and non-autistic individuals. Rosenblum et al. (2016) studied children aged 9 to 12 using three writing tasks (writing their own name, paragraph copying, and free-style writing) on a graphic tablet. Autistic children were significantly slower in handwriting fluency than non-autistic children. Similarly, Li-Tsang et al. (2018) found that autistic children aged 12-18 were slower in handwriting fluency than their non-autistic peers. Given the importance of handwriting skills (Graham et al., 1998), researchers have investigated factors influencing handwriting in autistic children. Hellinckx et al. (2013) examined full-scale IQ, visuomotor integration tasks, and Movement Assessment Battery for Children to assess their impact on handwriting fluency, measured by the number of letters written in 5 minutes. They found that autistic children had slower handwriting fluency than non-autistic children, with handwriting quality and speed being predicted by age, gender, and visuomotor integration. Handwriting difficulties also persist into

adulthood for autistic individuals. Godde et al. (2018) studied handwriting fluency by having participants copy a text for 5 minutes. They also measured finger dexterity (finger tapping), graphomotor skills (figure copying), and visuomotor integration skills (drawing a line inside a path). Consistent with previous studies, autistic individuals were slower in handwriting fluency compared to non-autistic individuals. Additionally, this study highlighted that handwriting fluency in autistic individuals was influenced by finger dexterity, graphomotor skills, and visuomotor integration. Given the importance of the sensorimotor component in handwriting, the following sections will discuss the relationship between sensorimotor skills and literacy skills in autistic children aged 7 to 11 years old.

Sensorimotor and Literacy Skills

Emerging evidence had found a close relationship between motor and literacy skills in autistic children, starting from early childhood (Bedford et al., 2016; Charman et al., 2017; Leonard et al., 2015). The relationship between motor and literacy skills was also found in non-autistic children (Lê et al., 2021). The onset age of motor functioning in young autistic children was found as a predictor of later language development (Bedford et al., 2016; Bhat et al., 2020). A longitudinal study by Bedford et al. (2016) examined whether gross motor skills, particularly the onset of walking, predict language development in 209 autistic children aged 2 to 5 years old, using regression analysis. The results indicated that autistic children's onset age of walking (parent reported) predicted the later language development. Additionally, gross motor score, using the Mullen Scales of Early Learning (MSEL), was a significant predictor of both expressive and receptive language development in young autistic children. Walking enhances children's visual access to elevated objects and caregivers' face,

while they are engaging with the environment (Iverson et al., 2018). Infants who start to walk can explore the environment with more interaction and frequency, spending more time in motion and conducting goal-directed movement more efficiently (Adolph et al., 2012). The increased opportunities to explore, assess and manipulate objects, allow children to initiate and spend more time in social communication, producing more vocalisation and gestures which aiding language development.

Fine motor skills were also found to have a significant relationship with both receptive and expressive language development. For instance, a study by Choi et al. (2018) investigated fine motor skills, using MSEL, on their later expressive language outcome in 71 infants with high-risk of autism. Even accounted for other variables (i.e., nonverbal IQ, gender, and socio-economics status), fine motor skills remained a significant positive predictor for later expressive language outcomes. These findings highlighted that both gross and fine motor skills were found to be predicting language outcomes in young autistic children. Additionally, a longitudinal study by Hellendoorn et al. (2015), examined 64 autistic children (aged 1.5 to 4 years old) on their fine motor skills with their receptive and expressive language (both motor and language measures used MSEL). Findings suggested that in young autistic children: 1) early fine motor skills were a predictor of both later receptive and expressive language development; 2) visuospatial cognition was a mediator between fine motor and language skills. Although several studies have found the relationship between motor and language development, varying methodologies and aims have been found when investigating autistic children in different age groups. A study by Iverson et al. (2018) investigated infants at high and lower risk of autism and found that early motor skills could be a key predictive cue for the diagnosis of autism, as well as the subsequent

language development. Taken together, these findings highlighted the importance of early detection of fine motor and visuomotor-related skills in subsequent language skills in young autistic children.

Visuomotor integration in Literacy Skills

Specifically, visuomotor integration (VMI) is the terminology to represent visuomotor integration processes in the studies investigating school attainment (Cameron et al., 2012, 2016; Grissmer et al., 2010; Son & Meisels, 2006). Thus, VMI will be used in the following contexts when studies investigated literacy skills. Although it is known that visuomotor integration differences in autism affect behaviours such as aiming to targets (i.e., using a door handle), bouncing a ball, and copying a teacher modelling a movement (i.e., holding a pen), it is not clear if VMI differences in autism influence academic attainment as per non-autistic school-aged children (Grissmer et al., 2010; Son & Meisels, 2006). In non-autistic school-aged children, data from the Beery motor assessment tool (Beery VMI, 2010), which quantifies VMI proficiency (e.g., timing accuracy; copying accuracy) using sensorimotor tracing and copying skills, showed children who were more fluent at tracing symbols were also more fluent in handwriting (Cameron et al., 2012), and those who were more accurate at copying symbols were also more accurate and fluent at literacy skills such as more accurate in letter-word identification and reading comprehension, and more fluent in handwriting (Cameron et al., 2012; Carlson et al., 2013; Grissmer et al., 2010).

In terms of sensorimotor tracing, VMI is related to the process of coordinating small finger movements in the hand (Cameron et al., 2012) to control a pen/pencil and integrating this sensorimotor information with the visual information (i.e., visual feedback) that is guiding the pen/pencil to accurately trace a letter (Schmidt, 1975;

Wolpert & Flanagan, 2001). Based on Schema Theory (Schmidt, 1975; 2003), visual and sensory information from the environment (e.g., location of an effector; target; size and weight of the tool) are integrated to allow time for visual feedback to be processed to make corrections (Elliott et al., 2010) to a performed action. This process is regarded as visual-motor coordination (VMC), which is conceptualised as fine motor coordination with visual feedback of the expected and current action (Carlson et al., 2013; Georgopoulos & Grillner, 1989), and is involved in tasks such as tracing and finger tapping (Davis & Matthews, 2010; Korkman et al., 2007). In school settings, VMC skills are involved in attainment tasks such as those that involve tracing letters or numbers in pencil-and-paper tasks or drawing shapes and objects. For example, to trace a letter (e.g., a E) children perform multiple stages that require the integration of motor and visual information: 1. coordinate small finger movements to grasp and control a pen/pencil; 2. plan a hand movement to locate the pen at the start of the letter; 3. execute the first letter stroke; 4. during the movement they are required to anticipate the directional change in the form of a letter; 5. plan the second movement based on the directional change in the letter; 6. execute the second movement; 7. plan to stop the movement at the end location. In terms of literacy, children who are more accurate at moving a pen to trace the path through a trail sequence (i.e., draw either a straight or curved line between two points) are more accurate when writing a letter (e.g., an F) and word (e.g., fox) during handwriting tasks (Kaiser et al., 2009). The transfer (see Schmidt, 1977; 2003; Elliott et al., 2010) of performance from tracing to handwriting is suggested (Kaiser et al., 2009; Tseng & Murray, 1994) be based on the acquisition of domain general sensorimotor processes that were recruited to control fine motor movements [i.e., precision of small finger movements to utilise a tool (e.g., pen/pencil)] and associated visual feedback processing.

In terms of sensorimotor copying, VMI is related to creating motor and sensory representations of an image and replicating it with the organisation of small finger movements as well as the processing of visual stimuli (Carlson et al., 2013). Motor and sensory representations of a to-be-copied image (e.g., “letter” or “word”) are formed during and after the observation of the image (Bandura, 1989; Byrne & Russon, 1998). Advance knowledge from the visual and sensory information in the environment, will be used in motor planning during movement execution. At the time of movement planning, an efferent copy of the to-be performed action (e.g., copy the letter with the correct length) and its correction is made in the central nervous system (Wolpert & Flanagan, 2001). The motor and sensory representations of the predicted action have been referred as internal action models (Elliott et al., 2010). These representations are subsequently used to control imitation (i.e., copy) of the word using small muscle movements on the hand to move the pen/pencil. During imitation, visual feedback from the moving hand (object position; direction; speed) is processed and integrated into the hand movement to make movement corrections (Elliott et al., 2010). This process is regarded as visual-spatial integration (VSI), which is involved in tasks such as handwriting and copying words/shapes on a sheet of paper or tablet (Carlson et al., 2013; Davis & Matthews, 2010). In a school setting, VSI skills are involved in school attainment tasks, such as copying images of letters or numbers in pencil-and-paper tasks. During a version of these copying tasks, children were required to pay attention to the spatial form of different novel shapes presented on the screen of a tablet. When a shape disappeared from the screen, the children were required to use a stylus pen to reproduce (i.e., recall and copy from memory) the shape as accurately as possible by drawing on the tablet (Waterman et al., 2014). Correlation analyses showed that children who demonstrated better copying skills were also significantly more accurate

at writing (r = 0.42) and reading (r = 0.32), and importantly for literacy performance reading and writing were significantly correlated (r = 0.53).

The transfer from copying to literacy-related skills (e.g., word reading, reading comprehension and handwriting) is suggested (Waterman et al., 2014; Wolf et al., 2009) to be underpinned by domain general sensorimotor processes (e.g., attentional, intentional, and sensorimotor processes) that are recruited and control copying and orthographic and memory process that are engaged during writing (Medwell et al., 2009). For example, during copying, which is voluntary imitation or imitation learning, attentional, intentional, and sensorimotor processes are engaged to create new internal action plans related to the observed stimulus (i.e., a symbol; a letter; or a person) (Iacoboni, 2009; Keysers et al., 2018; Schaal et al., 2003). Observing a symbol (e.g., triangle) enables an individual to represent the spatial properties of the symbol/letter within a sensorimotor system linking perception with action (Becchio et al., 2007). The resulting representations are used by sensorimotor planning processes to form forward and inverse models (Wolpert & Kawato, 1998), and generate an action plan (i.e., a motor command). During overt motor reproduction, efferent and reafferent sensorimotor information is integrated and processed by feedforward and feedback control mechanisms to support sensorimotor control, and the consolidation of a sensorimotor action in both tracing and copying activities. Across repeated imitation attempts, by comparing predicted and actual outcomes, sensorimotor action plans are updated (Buccino et al., 2004; Carroll & Bandura, 1990) such that reproduced movements are more accurate and closer to the biological kinematics displayed by a model.

Summary and Research Questions

Research suggests that visuomotor integration (VMI) plays a crucial role in children's skills development, including social skills (Cameron et al., 2012; 2016) and may also benefit academic competencies such as literacy skills (Carlson et al., 2014). While there is a growing body of evidence elucidating the relationship between sensorimotor processes and literacy in typically developing children (Carlson et al., 2013; Grissmer et al., 2010; Waterman et al., 2014) as well as those with developmental coordination disorder (De Waal et al., 2018; Fletcher-Flinn et al., 1997), there remains a gap in understanding VMI in relation to literacy skills, such as word reading, reading comprehension, and handwriting, in autistic children.

To address this gap in the literature, this PhD aims to investigate whether higher proficiency in VMI among autistic children aged 7 to 11 years is associated with enhanced literacy skills. By employing assessments specifically targeting tracing tasks (VMC) or copy-a-figure tasks (VSI), we aim to differentiate these two distinct skills and assess their individual contributions to literacy achievement. This study is also to investigate underlying differences sensorimotor control during VMC and VSI tasks in different planning positions in autistic children aged 7 to 11 years. Children's performance in VMC and VSI tasks will be assessed through kinematic analysis. The research questions of this PhD are:

1. Are sensorimotor control and learning differences prevalent in autism across life span?

   It is hypothesised that autistic individuals have sensorimotor control and learning differences, compared to non-autistic individuals. These differences are prevalent across life span.

2. Do sensorimotor planning and performance markers predict literacy skills in autistic children aged 7 to 11 years old?

It is hypothesised that sensorimotor planning and performance markers are predictors of literacy skills in autistic children aged 7 to 11 years old.

3. What are teachers' beliefs, knowledge and frequency of activities of sensorimotor skills, compared to literacy and maths skills, in autistic children aged 7 to 11 years old?

It is hypothesised that teacher had more beliefs and knowledge and engage their pupils more frequently in activities of literacy and maths skills, compared to sensorimotor skills in autistic children aged 7 to 11 years old.

Chapter 2: Methodology

Study Approach:

In my PhD programme of work, a mixed methods approach was adopted to systematically investigate the specified research questions. A mixed methods approach involves the selection and implementation of both qualitative and quantitative research methods within a single study or a series of studies (Creswell, 2003). This approach is particularly suitable for studies aiming to provide a comprehensive analysis of complex phenomena because the information obtained from qualitative and quantitative research approach complements each other, thus contributing to a more nuanced understanding of the research questions (Farquhar et al., 2011).

Qualitative research, defined as “an iterative process in which improved understanding to the scientific community is achieved by making new significant distinctions resulting from getting closer to the phenomenon studied” such as interviews, focused groups or systematic literature reviews (Aspers & Corte, 2019, p.139). This definition highlighted the importance of qualitative methods to explore concepts or methods of a phenomenon, and to identify the trend (Thelwall & Nevill, 2021). As for quantitative research, a range of methods concerning a systematic examination of a phenomenon is conducted with statistical methods (Watson, 2015). Statistical or numerical data are collected using measurements (Watson, 2015).

In the current PhD programme of work, qualitative method (i.e., a systematic review), was used to explore whether autistic individuals had sensorimotor control and learning processes differences, compared to the non-autistic individuals. Narrative

synthesis was used to explore this phenomenon. Quantitative methods, such as cross-section study, experimental study, and survey, were used to explore: 1) whether VMI (using standardised measures), sensorimotor performance and planning markers are predictors of literacy skills in autistic children aged 7 to 11 years old; 2) sensorimotor control differences in autistic and non-autistic children aged 7 to 11 years old; 3) teachers' beliefs, knowledge and frequency of activities in motor skills of autistic children aged 7 to 11 years old. A mixed methods approach was appropriate as it explore the phenomenon of the sensorimotor differences in autistic individuals (qualitative), then to confirm and test the differences through measurements (quantitative) and finally to explore the implication of sensorimotor behaviours in a school setting, via measuring teachers' beliefs, knowledge, and frequency of activities in motor skills.

Study 1: Sensorimotor Control and Learning in Autistic Individuals: A Systematic Review

A systematic review was conducted as the initial study in this PhD program to explore sensorimotor control and learning processes in autistic individuals across their lifespan. By systematically gathering and analysing existing studies, the review identifies key gaps, limitations, and strengths in the current literature (Denyer & Tranfield, 2009). These insights are crucial as they highlight areas that require further investigation, thereby shaping the specific research questions for the PhD. Moreover, the synthesis of data from various studies in this systematic review provided a comprehensive understanding of the current state of knowledge of sensorimotor control and learning in autism, which informed the experimental designs (e.g., number of trials, type of practice and number of participants) and movement outcomes and

production measures (e.g., movement time, total error and peak velocity). The information generating from this systematic review guided the design of new studies to avoid past pitfalls and build on successful strategies (Munn et al., 2018). Before conducting the current systematic review, it is crucial to verify if any previous reviews have explored the same area and identify existing research gaps. A new systematic review can then be carried out to evaluate the landscape of the phenomenon (Craig et al., 2008).

Several systematic reviews, such as those by Healy et al. (2018) and Ruggeri et al. (2020), have studied various motor interventions in autistic children, providing an overall view of their effectiveness. A meta-analysis by Fournier et al. (2010) investigated motor coordination in autistic individuals, focusing on gait, arm movement, and postural stability. Nevertheless, these studies did not include enough kinematic analysis to examine differences in sensorimotor control and learning processes in autism. Additionally, Fournier et al. (2010) was conducted more than a decade ago and mainly concentrated on gross motor coordination, with only one study addressing fine motor coordination. To fill these gaps in the current literature and achieve a more comprehensive understanding of sensorimotor control and learning processes in autistic individuals, a new systematic review (Study 1) was conducted. The included studies were synthesised using a narrative synthesis technique, which assessed and discussed the phenomenon of sensorimotor control and learning processes in autism.

Study 2: Visuomotor Integration and Literacy Skills in Autistic Children aged 7 to 11 years old

The findings of study 1 (the systematic review) indicated that sensorimotor control processes were prevalent in autism across life span. These control differences in autism also present in various domains, such as daily living skills and school attainment skills (Miller et al., 2024). Specifically, the visuomotor integration skills (i.e., the ability to integrate visual information and motor functioning) are closely related to literacy skills (i.e., reading and writing) in early years and school-age children (Cameron et al., 2012, 2015; Kim et al., 2018). Currently, limited studies have focused on VMI and literacy skills in autistic children aged 7 to 11 years old. Moreover, it remains unclear in the literature that whether VMI is a predictor of literacy skills if accounting for other cognitive measures such as executive function. Therefore, in study 2, a cross-section study on the visuomotor integration (VMI) skills and literacy skills in autistic children aged 7 to 11 years old, was conducted.

A cross-sectional study is an observational study that analyse data from a population at a single point in time (Wang & Cheng, 2020). This quantitative-based study enables researchers to analyse the prevalence and relationships between various variables (e.g., VMI and literacy skills) within a specific timeframe. One of the advantages of the cross-sectional study is its efficiency in terms of time and resources. In study 2, standardised assessments of VMI, IQ, EF and literacy measures were used with autistic children aged 7 to 11 years old. Sixty-two participants were recruited, and the data collection processes lasted for 6 months. Correlation analysis was conducted to understand the relationship between VMI and literacy skills. Additionally, to explore the predicting effect of VMI, hierarchical regression analyses were conducted. The

hierarchical regression analysis involves the procedure to entering predictor variables into the regression model in a predefined order based on theoretical or empirical considerations. By adding variables in steps, hierarchical regression allows researchers to assess the unique contribution of each set of predictors after accounting for the influence of the variables entered in earlier steps (Richardson et al., 2015). Hierarchical regression analyses enable researchers to 1) examine models by specifying the order in which variables are entered into the regression equation. This method helps in examining the causal ordering and the incremental value of new predictors; 2) variance were explained for each new predictor put into the regression equation, after accounting for the variance explained by previously entered variables. This facilitates understanding the importance of different predictors; 3) control for confounding variables and control variables; 4) enable researcher to compare nested models to assess whether the addition of the new predictor improves or decreases the model's explanatory power (McCandless et al., 2012; Richardson et al., 2015; Witte et al., 1994).

Due to the methodological and practical advantages of to conduct a cross-sectional study, as well as answer the research question on the relationship between VMI and literacy skills, and whether VMI was a predictor of literacy skills in autistic children aged 7 to 11 years old, a cross-section study was chosen and conducted.

Study 3. Visuomotor Control and Predictors of Literacy Skills in Children aged 7 to 11 years old

In study 3, different data analyses were conducted to answer different research questions: 1) are there any sensorimotor control differences in autistic children,

compared to non-autistic children aged 7 to 11 years old? 2) what are the predictors of literacy skills in children aged 7 to 11 years old?

To answer the first research question in study 3, a 2 group (autistic vs nonautistic individuals) x 2 tasks (copy vs trace) x 3 symbols (line vs cross vs triangle) mixed design repeated measure ANOVA was conducted to investigate the mean differences of sensorimotor control planning (e.g., percentage time to peak velocity) and performance (e.g., total movement time) markers. Repeated measures ANOVA (Analysis of Variance) is a robust statistical method used to compare means across multiple observations collected from the same subjects under varying conditions or at different time points (Armstrong, 2017). One advantage of this method is its capability to accommodate variability within-subjects, which improve statistical power and sensitivity to detect differences. By using the same participants across all conditions, repeated measures ANOVA effectively controls for individual differences (Snedecor & Cochran, 1980). In study 3, group was between-subject, to answer the question whether autistic children were different from non-autistic children on the planning and performance markers. Tasks and symbols were within subject, that both autistic and non-autistic children performed copying and tracing activities across all 3 symbols.

After analysing the mean differences of sensorimotor planning and performance markers in autistic and non-autistic children, correlation and hierarchical regression analyses were conducted to explore the predictors of literacy skills in children (both autistic and non-autistic children). Similar data analysis processes of study 2 were undertaken in study 3. The novelty of the study 3 was that the VMI planning and performance markers that were chosen to represent the underlying motor mechanisms,

were investigated in both correlation and regression analyses. This finding highlights the relationship between VMI planning and performance markers, and literacy skills in autistic children aged 7 to 11 years old; as well as expanding the current literature on not just the VMI standardised assessment, but also the underlying motor mechanisms predicting literacy skills in autistic children aged 7 to 11 years old.

Study 4. Teachers' Beliefs, Knowledge, and Frequency of Activities of Motor Skills in 7- to 11-year-old Autistic Children in the United Kingdom

Study 4 aims to document a newly developed survey on schoolteachers' beliefs, knowledge and frequency of activities in autistic children aged 7-11 years from mainstream and special education needs schools in the United Kingdom. This survey was developed to explore teachers' beliefs and knowledge of motor skills, which informed their teaching methods (Blömeke et al., 2014), and how frequent they do motor-related activities in the school setting.

As this was a novel survey, It is important to know whether participants are answering what we are designed to measure (hence whether the measurement instruments are valid) (Knekta et al., 2019). Exploratory and confirmatory factor analyses (EFA/CFA) were assessed to test the survey psychometric properties, to ensure the reliability and validity of the new survey (Mulaik, 1987). Both EFA and CFA were conducted with R studio (Beaujean, 2013), as it is a flexible and powerful language allowing factor analysis to 1) examine the data's properties, 2) check any model assumptions and 3) conduct EFA followed by CFA without exporting or write syntax in other programme's language (Kelley et al., 2008). This had significantly reduced human error in data analysis (Beaujean, 2013). When there was inconsistency

between what the survey intended to answer, and teacher's answers, the survey item were appraised and inspected through the parameters and its theoretical justification.

After the survey were checked with its reliability and validity using EFA & CFA, three one-way ANOVA was conducted to examine the mean difference significance of teachers' beliefs, knowledge, and frequency of activities in motor skills, compared to literacy and maths skills. To further investigate the factors that may predict teachers' beliefs, knowledge, and frequency of activities of motor skills, hierarchical regression analyses was conducted to examine the incremental contribution of different sets of variables to the prediction of a dependent variable (Richardson et al., 2015).

Chapter 3: Sensorimotor control and learning in autistic individuals: A systematic review

Introduction

As indicated in the previous chapter (i.e., general introduction and literature review), autistic individuals have difficulties or delays in sensorimotor control and learning processes such as fine motor, gross motor, postural control and motor planning (Biffi et al., 2018; Landa et al., 2022). These delays may affect other skills (e.g., social skills, language skills and academic skills). It is important to investigate the underlying motor mechanisms, using movement outcomes and production measures (e.g., reaction time, movement time and kinematic analysis). A systematic review was conducted to investigate sensorimotor control and learning processes in autistic individuals.

In the current literature, numerous systematic reviews (e.g., Dillon et al., 2016; Healy et al., 2018; Ruggeri et al., 2020) examine various types of motor intervention with autistic individuals. These reviews mainly focus on the effects of motor intervention on motor outcomes (Dillon et al., 2016; Healy et al., 2018; Ruggeri et al. 2020; Sowa & Meulenbroek, 2012); on social/behaviour/cognitive outcomes in autistic children and adolescents (Bremer et al., 2016; Lang et al., 2010; Sowa & Meulenbroek, 2012; Tan et al., 2016); on motor activity/imitation limitations (Downey & Rapport, 2012; William et al., 2004a); and on equine therapy interventions (Srinivasan et al., 2018) in autistic individuals. Previous reviews focus on autistic children and adolescents (e.g., Bremer et al., 2016; Dillon et al., 2016; Ruggeri et al., 2020). Some reviews cover the life span of autistic individuals and find that most participants were in the age range of 10-15

years (adolescents) (Lang et al., 2010; Sowa & Meulenbroek, 2012). Also, the above literatures on motor and physical activity interventions mainly focus on the effectiveness of the interventions, such as the general motor outcomes (e.g., fine and gross motor skills scores) in autism, measured by standardised motor assessment tools (e.g., MABC-2). These tools provide only basic information on movement outcomes (e.g., accuracy in catching a ball or total time to stand on a balance beam), so the motor control processes remained unclear. Motor control measurements (e.g., reaction time and force production measures) and kinematic analysis (e.g., peak acceleration and peak velocity) are used to reflect the motor control processes.

To this end, the purpose of this review is to comprehensively examine sensorimotor practice protocols on motor control and learning in autistic individuals, using sensorimotor outcomes (e.g., movement time and variability; error) and production measures (e.g., force production) and kinematic analysis (e.g., peak velocity), as there is a clear research gap since few studies have synthesised kinematic analysis evidence in sensorimotor tasks in autism. Thus, a systematic review was conducted on the effects of sensorimotor practice protocols on motor performance and learning in autistic individuals, compared to non-autistic individuals. Finally, after synthesising the identified material, the current review proposed to generate data-based conclusions about studies that investigated motor control and learning processes for autistic individuals and highlighted potential gaps that could be addressed in future research.

The three review questions were:

1. Do sensorimotor control processes distinguish autistic individuals from non-autistic individuals?

2. Do sensorimotor learning processes distinguish autistic individuals from nonautistic individuals?

3. Do autistic sensorimotor control and learning processes adapt as a function of practice?

Methods

This systematic review was organised according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses standards for systematic review (PRISMA; Moher et al., 2015) and was registered on the Open Science Framework. The registration DOI is https://doi.org/10.17605/OSF.IO/ZQ3X2.

Search Strategy

The current systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009). Search terms were formulated and defined following a thorough examination of literature associated with autism, motor control and learning, and practice aligning with the objectives specified in the systematic review. These terms underwent preliminary testing across selected search engines, after which they were refined to ensure a broad spectrum of literature for subsequent evaluation. A comprehensive search of seven databases (PsycINFO, PubMed, Web of Science, Scopus, Google Scholar, OSF Preprints and PsyArXiv) from 1990 to April 2021 was performed by me, the primary researcher, using the following search terms: [autism OR AUTISM OR ASD OR “Autism Spectrum Disorder”; AND sensorimotor OR sensory-motor OR motor*; AND kinematics OR kinematic*; AND “motor control” OR “motor learning” OR retention OR acquisition OR practice]. Filters were applied for published

journals from 1990-2021, and English language journals. No filters were applied for age of participants to include as many studies as possible. Finally, the backwards snowballing technique (i.e., using the reference list of included articles to identify new papers to include) was carried out to include as many studies as possible (Wohlin, 2014).

Selection Criteria

Selection criteria were based on the research aims of this systematic review. Studies were included based on the following inclusion criteria: (1) studies published from 1990 to 2021; (2) participants had a clinical diagnosis of autism spectrum disorder, autism, or Asperger's syndrome, and if a study compared multiple clinical groups (e.g., ADHD), only the results from the autistic, and non-autistic, individuals were included; (3) an intervention that a) contained a motor task where sensorimotor performance and/or learning was examined in autistic and non-autistic individuals; b) had quantified at least one sensorimotor outcome and/or production measure: sensorimotor outcomes (e.g., motor timing and motor variability), sensorimotor control (e.g., reaction time), and kinematic analysis (e.g., peak acceleration and peak velocity); (4) a control group of non-autistic individuals; (5) published in English.

Studies were excluded based on the following criteria: 1) sensorimotor performance and/or learning was measured using general movement assessment methods, such as Movement Assessment Battery for Children (MABC-2), Bruininks Oseretsky Test of Motor Proficiency (BOT-2), or Vineland Adaptive Behaviour Scale-II (VABS-II), general movement assessment methods that were valid standardised developmental motor assessments that quantify motor skills or identify and describe

impairments of motor performance but were not designed to measure the underlying sensorimotor control and learning processes, thus they did not align with current research aims; 2) systematic reviews, meta-analyses, conference proceeding, abstracts or a technical report.

Data Extraction

I, as the primary researcher, and another reviewer (TC) in my research group independently performed aspects of the data extraction process of the captured studies. First, I removed duplications and used the selection criteria (see below) to screen studies. Subsequently, the titles and abstracts of the studies were reviewed. There were 1,395 studies after the duplication process was completed, and then two reviewers independently checked 10% of the studies (*n*=140) using the title and abstract. The inter-rater reliability (McHugh, 2012) between me and TC was 93%, which confirmed the selection criteria was reliable. I then conducted a full-text review of the included studies to gather the detailed information required during data extraction for a narrative synthesis. TC conducted a full-text review of 10% of the final selected studies. I and TC discussed these studies, with six studies requiring a resolution discussion with a third author (SH).

To meet the research aims of the systematic review, the following data were extracted from each final included study to generate a narrative synthesis on: 1) group characteristics: autistic group [number of participants, gender, age (mean and range), diagnosis condition and intelligence quotient (mean, range and measures)], non-autistic group [number of participants, gender, age (mean and range) and intelligence quotient (mean, range and measures)]; 2) study characteristics: task type, practice

structure and total number of trials; 3) movement outcome and production measures: movement outcome, motor control and kinematic outcomes. Following the extraction of the above descriptive information, the resulting information was extracted: within-group differences (i.e., pre- and post-test in autistic or non-autistic group); between-group differences at post-test (i.e., autistic vs nonautistic group); if it included retention test, within-group differences from post-test to retention test, and between-group differences at retention test.

Missing Data

In the event that data was missing, a corresponding author from a published included article was contacted when data [e.g., means and standard deviations (SDs)] was missing on key measures of movement outcome (e.g., total movement time and variability), sensorimotor control (e.g., reaction time and grip force), and kinematic analysis (e.g., peak acceleration and peak velocity). Moreover, if data from post-tests or retention tests were not available in the paper, only the sensorimotor performance (i.e., data from pre-test to the end of practice) data was processed. The relevant corresponding author was also contacted if there was missing data about other methodological characteristics of a study (e.g., number of trials). Studies were not excluded if information was missing about other general group characteristics such as cognitive measures, age, and gender. This missing information was appraised in the limitations section of this study.

Assessment of Risk of Bias

The ROBINS-I tool, which stands for Risk of Bias in Non-randomised Studies of Interventions, was utilised to assess the risk of bias in all studies included in the

analysis (Sterne et al., 2016). This tool evaluates studies across seven domains of bias, each accompanied by specific guiding questions: 1) potential bias due to confounding factors; 2) bias in the selection of study participants; 3) bias in the classification of interventions; 4) bias due to deviations from intended interventions; 5) bias due to missing data; 6) bias in the measurement of outcomes; and 7) bias in the selection of reported outcomes. Each domain was graded on a scale including “Yes”, “Probably Yes”, “No”, “Probably No”, “No Information”, and “Not Applicable”. Following the guidance provided by Sterne et al. (2016), an overall risk of bias rating – categorised as low, moderate, serious, or critical—was assigned to each study after synthesising all items within each domain. Overall judgments were determined by considering the highest rating assigned within any individual domain, consistent with ROBINS-I guidelines. To ensure consistency and reliability, interrater reliability was assessed between me and TC) using Cohen’s Kappa score, yielding a score of 91%, indicating almost perfect agreement.

Quality of Study

The quality of included studies was assessed using a checklist forwarded by Kmet et al. (2004) as it was recommended for systematic reviews that include quantitative studies. Each study included in the analysis was evaluated against a 14point criteria, with scores assigned as 0 (No), 1 (Partial), 2 (Yes), or non-applicable (N/A) based on adherence to each criterion. To establish an overall “quality score” for each study, two calculations were performed. Firstly, a ‘total sum’ score was computed using the formula: [(number of “yes” * 2) + (number of “partials” * 1)]. Secondly, a ‘total possible sum’ was determined as: [28 - (number of “N/A” * 2)]. Given that not all 14 items were applicable to every included study, an individual quality score was derived

by dividing the ‘total sum’ by the ‘total possible sum’. Quality scores for individual studies ranged from 0 to 1, with scores below 0.5 indicating limited quality, 0.5 to 0.7 indicating adequate quality, 0.7 to 0.8 indicating good quality, and scores exceeding 0.8 indicative of strong quality (Kmet et al., 2004). To ensure methodological rigor, quality assessment for 10% of included studies was independently conducted by a second coder (TC), yielding an inter-rater reliability score of 83%. Additionally, Cohen’s Kappa score was employed to assess interrater reliability between me and TC.

The Overall Quality of Evidence

The overall body of evidence for movement outcomes and production measures (e.g., motor control and kinematic markers) was intended to be conducted using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) framework (Goldet & Howick, 2013). GRADE is a well-developed and widely used framework for assessing the quality of evidence of studies in systematic reviews. In this framework, each different study outcome is assessed separately based on GRADE criteria. The included studies were experimental studies on sensorimotor control and learning in autistic compared to non-autistic individuals. Since the autism group serves as the experimental group, randomization between groups is not feasible. Hence all included studies are N-RCT. They are all initially assigned a “low grade” due to inherent limitations in the GRADE criteria. Subsequently, based on upgrade criteria (e.g., large effect size, dose-response relationship, and plausible confounding factors), the quality of evidence is categorised as “high”, “moderate”, “low”, or “very low”.

Nevertheless, upon completion of the review, it became evident that although the included studies addressed 15 different movement outcomes and production

measures (e.g., grip force, peak acceleration, and peak velocity), many of these outcomes were only examined in a limited number of studies. Furthermore, studies examining the same movement outcomes and production measures often employed different activities and varied in the number of trials conducted with different types of practice. For example, both studies examined reaction time. One study used gait as the activity, and another used reach and grasp tasks. The heterogeneity observed among the included studies in terms of the types of movement outcomes assessed and the activities employed further complicates the application of GRADE criteria. This diversity makes it difficult to effectively compare and synthesise the findings from different studies. Consequently, while GRADE is an important tool for evaluating evidence quality in systematic reviews, it is not suitable for this review due to these challenges.

Effect Sizes

Effect sizes were not calculated for each movement outcome and production measure across studies in this systematic review. This decision was influenced by the variations observed among the types of sensorimotor tasks examined in each study. The included studies exhibited diversity in terms of task types, practice types, number of trials, and activities. Consequently, due to the heterogeneity reviewed from these studies, effect sizes were not calculated.

Data Synthesis

Regarding data synthesis, a narrative synthesis was conducted by me, supported by review and discussion with SH and TC. This process involved extracting key information from all included studies associated with the review questions.

Results

Study Selection

As illustrated in Figure 3, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; Liberati et al., 2009) diagram described the detailed study selection process. A total of 1,739 records were identified from the database searches using the specified search terms. First, 344 duplications were removed leaving 1,395 studies available for title and abstract screening. This led to 429 records being full-text screened, which resulted in a total final number of 97 studies included in the review. The publication year of the included studies ranged from 1993 to 2021, and it appeared that the topic received increased attention in recent years; for example, 48 of the included studies (50%) were published between 2016 and 2021.

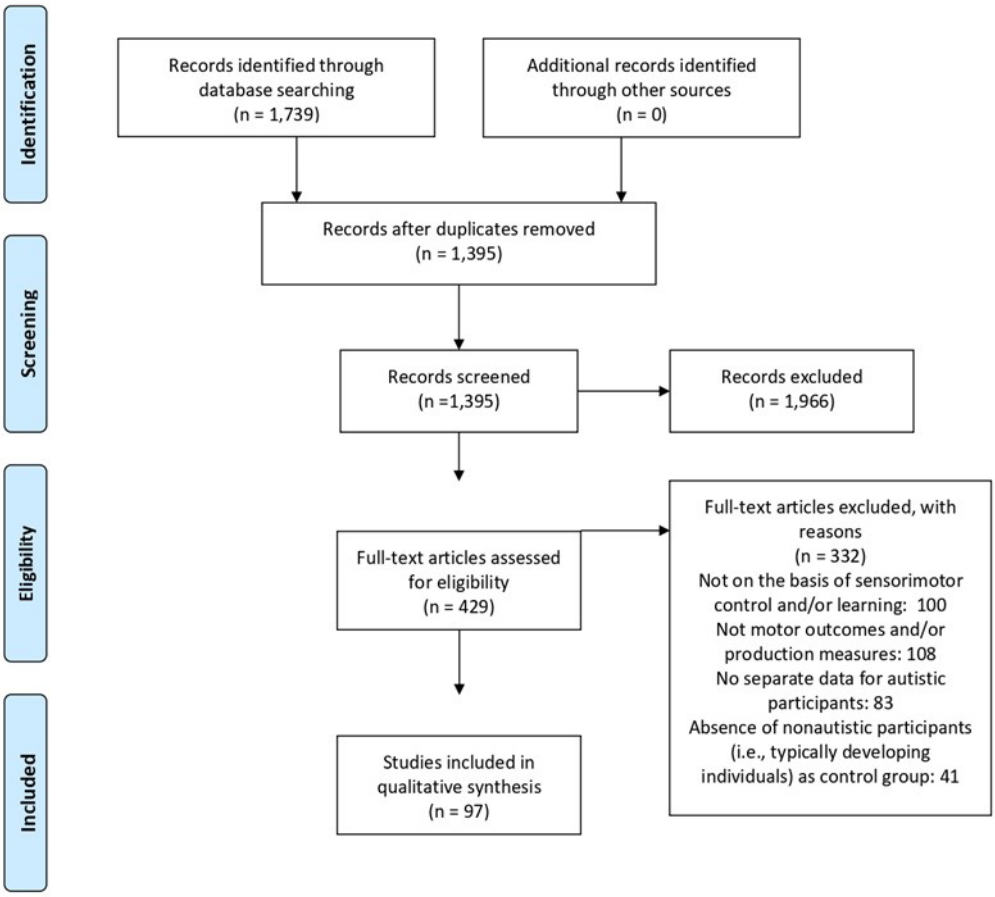

Figure 3. PRISMA flow chart illustrating the process of study selection.

Participants

Table 1 presented a summary of autistic participants' information (e.g., mean age range, number of studies and participants) of all the included studies (*n*=97). A total of 1,971 autistic volunteers participated in the 97 included studies. Within the SR and based on accepted age category definitions (see Singh et al., 2019), these participants were categorised into three age groups: children (0.0-9.11 years), adolescents (10.0-19.11 years), or adults (20+ years). The age distribution was relatively similar with 30% being children, 45% being adolescents and 25% being older than 20 years. The overall male–female gender ratio was 8:1. In terms of the reported cognitive measure scores, 69% of participants had scores over 90, which was reported

as being average or above average (Rommelse et al., 2015) (see Table 1: 100-110 = 34%; 110+ = 35%). Most of the participants matched with the non-autistic control group in age, gender or cognitive measures (90%). Three studies were conducted with both autistic children and adolescents (Papadopoulos et al., 2012; Rinehart et al., 2001, 2006a). One study was conducted with both autistic children and adults (Cavallo et al., 2021). Also, only two studies (Forti et al., 2011; Mussey & Klinger, 2020) were conducted with autistic participants in the age group of infant/toddlers (0-3 years). In this systematic review, these two studies were combined within the age group of children. Ten studies did not report any information on the age, including mean age, SD and range.

Table 1. Autistic volunteers that participated in the included studies: age range, number of studies and participants, gender, cognitive measures, and criteria of matched control group

Mean age range (years and months)	No. of studies and total number (n) of participants	Gender ratio (M: F)	Cognitive measures: mean scores range percentage (mean score range in cognitive measures) (%) of participants within a control group	Matched control group and and percentage (%) of participants within a range
0-9;11	26 (n=470) 3 studies use both children and adolescents 1 study use both children and adult	4:1	FSIQ: 80-90 (27%) 90-100 (36%) 100-110 (1%) 80-90 (31%) Verbal IQ: 85.0-114.9 (2%) Not reported (3%)	Age matched (35%) Gender matched (3%) IQ matched (4%) Age and gender matched (49%) Age, gender and IQ matched (6%) Not matched (2%) Not reported (1%)
10;0-19;11	43 (n= 953)	7:1	FSIQ: 80-90 (13%) 90-100 (24%) 100-110 (41%) Nonverbal IQ (2%)	Age matched (7%) Gender matched (12%) Age and IQ matched (20%) Age and gender matched (35%) Age, gender and IQ matched (23%)

			Raven SPM (2%) Not reported (18%)	Not matched (3%)
20;0+	22 (n=357)	5:1	FSIQ: 80-90 (8%) 90-100 (5%) 100-110 (27%) 110+ (40%) WASI IQ: 10-20: (10%) Raven SPM: 70-80: (4%) Not reported (6%)	Age matched (8%) Gender match (3%) Age and gender matched (12%) Age, gender and IQ matched (77%)
Studies didn't report age	10 (n=122)	10:1	FSIQ: 80-90 (4%) Not reported (96%)	Gender matched (46%) Not matched (54%)
Total	97 (n=1971)	8:1	FSIQ: 80-90 (9%) 90-100 (22%) 100-110(34%)	Age, gender *or* cognitive measures (90%) Age, gender *and* IQ matched (24%)

	110+ (35%)

Note: Only one study has a participant in the mean age of 40 years old, so we combined that together in the 20+ group as adults. There were 10 studies that did not report any information on the age, including mean age, SD, and range.

Risk of Bias

The risk of bias of each included study was evaluated using ROBINS-I tool (Sterne et al., 2016). Based on the nature of non-randomised control studies, most of the studies were judged as “Moderate” in domain 1. Most of the studies were rated as being of low risk of bias in domain 2, 3, 4, 5 and 7. In terms of domain 6, most of the studies did not report blinding of outcome assessors. The overall rating suggested that most of the studies were judged as “Moderate” in this systematic review.

Results of Reviewed Studies

The key study characteristics were illustrated horizontally across the top of Table 2 to facilitate the narrative synthesis to answer each review question on the topic of motor planning and motor execution. A textual narrative synthesis was selected as a method to provide a detailed commentary on study characteristics, context, quality and findings based on similarities and differences among studies (Barnett-Page & Thomas, 2009; Cleaver et al., 2021; Lucas et al., 2007) leading to the generation of a set of conclusions. The key characteristics were as follows: task types, practice types and total number of trials, sensorimotor behaviour measures (i.e., movement outcomes; motor control outcomes; kinematic measures), within group differences measured from pre-test to post-test, between group differences measured at post-test, between group differences measured at retention test, and quality of study (Kmet et al., 2004).

Table 2. Study characteristics, and movement outcomes and production measures

Author (s) (year)	Task type and brief description	Practice structure[a] and total number of trials	Outcomes			Within group differences from pre-test to post-test	Between group difference at post-test	Include retention Test (Y/N), if Y, within group differences from post-test to retention test, and between group difference	Quality of evidence (Kmet)
			Move-ment	Motor control	Kinematics				
Crippa et al. (2021)	Upper limb movement task Participants reached and grasped a ball placed over a support and dropped it in a hole.	Blocked (5 trials)	Total movement time Number of movement units	Wrist inclination	PV* TPV* PA* TPA* PD* TPD*	NR*	ASD VS TD: greater wrist inclination NR for other outcome measures.	N	0.81 (Strong)
Foster et al. (2020a)	Upper limb movement task Participants performed a visual motor sequence timing task (VSTT) by moving the cursor horizontally rightwards so that it was located in the middle target (segment 1), followed by a leftwards reversal to locate the cursor in the start circle (segment 2), and finally a rightwards reversal to move the cursor through the middle target and then stop in the righthand end target.	Blocked (30 trials)	Total error Total Movement time Relative timing		sdPA* sdPV*	From the first 6 trials to the last 6 trials: ASD: has less total error faster relative timing movement time	ASD vs TD: more total error longer relative timing in segment 3 greater sdPA	Y ASD: has less total error Between group: ASD: has more total error, has more sdPA	0.81 (Strong)
Foster et al. (2020b)	Upper limb movement task Participants were instructed to 'watch and pay attention to the dot's trajectory, with the intention to then copy the trajectory' by moving the cursor horizontally. They were also required to fixate gaze on a small white spot at the centre of a black circular target, which appeared randomly for 1000ms at each location of a standard nine-point grid.	Random and Blocked (60 trials- 2 conditions)			tPHV*	ASD_pre VS ASD_post: occurs earlier in tPHV in atypical model for random to block order occurs earlier in tPHV in atypical model from block-to-block order learning effect in the atypical model in random practice	ASD vs TD: slower in tPHV Non sig* for other outcome measures.	N	0.85 (Strong)
Wild et al. (2012)	Upper limb movement task Participants observed short video clips showing a human hand in 4 different conditions (normal, fast, short and elevated). Participants imitated when the exclamation mark appeared. Eye data were	Blocked (96 trials- 4 conditions)	Total movement time Movement amplitude		PV T%	NR	NR	N	0.77 (Good)

	obtained to allowed identification of gaze position co-ordinates at each target position.								
Mosconi et al (2013)	Upper limb movement task Participants completed a manual motor test in which they were presented with a pegboard of keyholes arranged in a 5×5 grid and with various orientations (Lafayette Instruments, Lafayette, IN). Subjects were instructed to insert a grooved peg into each slot with the proper orientation as fast as possible. Their dominant and non-dominant hands were tested separately. Time to completion and the number of times a peg was dropped were examined.	Blocked (200 trials for 5 conditions)	Total movement time Total error (the number of times a peg was dropped)				ASD vs TD: adapted at slower rate	N	0.81 (Strong)
Gidley Larson & Suchy (2014)	Upper limb movement task (Motor Sequence Learning Task) Motor sequence learning was assessed using a task based on the Push-Turn-TapTap (PTT) task from the Behavioral Dyscontrol Scale-Electronic Version. Participants sat in front of a computer screen and performed a complex motor sequence using the BDS-EV response console.The motor sequence consisted of three hand movements performed in the following order: Push (push joystick forward), Turn (turn joystick in a clock-wise direction), TapTap (tap the white dome two times). To examine the effect of types of verbalization on motor performance, there were three Verbalization Conditions: (1) Natural Learning (NL) Condition, (2) Task-Congruent Verbalization (TCV) Condition, and (3) Task-Incongruent Verbalization (TIV) Condition. After the three practice trials, the pictures of the movements and words disappeared. Participants were instructed to continue to perform the movements on their own, while saying out loud the words presented during the practice trials. In all conditions, if participants made an error, an audible beep sounded, and a picture of the correct movement was displayed on the screen; otherwise the screen remained blank. Participants received a short 1–2 min break between each Verbalization Condition.	Serial (31 trials per condition)	Total error (in single movement or movement sequence) Total movement time	Latency time between first and second tap		NR	ASD VS TD: less total error when TIV (see description of task) didn't affect by TIV longer movement time in natural learning condition	N	0.73 (Good)
Hayes et al (2016)	Upper limb movement task Participants were provided with general instructions to "watch and then copy the movement	Blocked (84 trials- 14 blocks)	Total movement time and variability Total error		PV %TPV*	ASD_pre VS ASD_post	ASD vs TD: greater timing variability;	N	0.85 (Strong)

	displayed by a white dot on the computer monitor". The model (i.e., a non-human agent model) displayed a single horizontal trajectory that originated from a home-target (diameter = 12.50 mm) positioned on the left-hand side of the screen and ended at a right-hand end-target (diameter = 12.50 mm), or right-hand end-space (i.e., no target; see below). To do so, the volunteer practised the task by performing typical goal-directed aiming movements using a hand-held stylus on a graphics tablet until a white dot/cursor (diameter = 6.25 mm), which represented the stylus, moved from the left-hand home-target to the right-hand end-target in 1700 ms.						decreased timing variability; Higher timing accuracy; increased PV	occurred later in %TPV		
Glazebrook et al. (2008)	Upper limb movement task Participants responded as quickly as possible to the precue light illuminating for 2s, followed by a random foreperiod of 1–1.8 s, by releasing the home switch and depressing the target switch with the appropriate hand.	Blocked (256 trials – 8 conditions)	Total movement time	Reaction Time			NR	ASD VS TD: longer total movement time longer reaction time	N	0.81 (Strong)
Forti et al. (2011)	Upper limb movement task Participants transported a rubber ball to a hole in which the ball was to be dropped.	Blocked (10 trials)	Total movement time Total error		Time to reach peak velocity Hand velocity		NR	ASD VS TD: longer total movement time; higher hand velocity	N	0.73 (Good)
Nazarali et al. (2009)	Upper limb movement task Participants responded as quickly as possible to the precue light illuminating for 1500ms, followed by a random foreperiod of 500–1100ms, by releasing the appropriate index finger from the home position and depressing the target switch.	Variable (80 trials)	Total movement time movement variability	Reaction Time			Nonsig	ASD vs TD: longer total movement time; more movement variability; longer reaction time	N	0.62 (Adequate)
Rinehart et al. (2001)	Upper limb movement task Participants began by depressing the first target button as quickly as possible in response to illumination of the LED in its base. s during reciprocating movements between buttons L and R, instead of moving back to L after depressing R, button R1 illuminated, requiring a reprogrammed response to the right. Alternatively, instead of moving on R after depressing L, button L1	Blocked (32 trials)	Total movement time Total error	Reaction time			ASD_pre VS ASD_post longer movement time; shorter reaction time;	Nonsig	N	0.73 (Good)

	illuminated, requiring a reprogrammed response to the left.								
Pearson (2020)	Upper limb movement task Participants were instructed to move their hand (mouse) to in and out of two defined target areas (Blue rectangle) on the screen in front of them.	Variable (36 trials- per condition)	Total movement time		PV PTPV Normalized jerk	NR	ASD VS TD: shorter total movement time	N	0.61 (Moderate)
Crippa et al (2013)	Hand-eye coordination (press and touch tasks) The children were seated at a desk. Each of them participated in three tasks: (1) In look, participants were required to look at a target in order to identify its colour, and fixation latencies from target onset to the first fixation in the target hemi-fiels were collected. (2) In press, participants had to indicate the target's left/right position on a button box, using their left index finger on the left button for left targets and the right index finger on the right button for right targets. RTs and fixation latencies were collected. (3) In touch, participants were required to touch the targets on the screen with a 40-cm-long stick held at the edge (this was used in order to keep a 60 cm distance from the eye tracker and avoid data loss). The children held a stick in each hand and used the ipsi-lateral hand to indicate the target; movements started from a set position by lifting the hand off a pad on the table.	Serial (48 trials for each task)	Touch time	Reaction time;		NR	ASD VS TD: weaker hand-eye correlation in press	N	0.73 (Good)
Salowitz et al (2013)	Hand-eye coordination task Participants stood and watched a 12-min "interactive" video of a demonstrator who faced the camera and performed a set of 52 different discrete non-meaningful gesture sequences with the hands and arms. Gestures were presented one at a time in video form so that the demonstrated "target" gestures were the same for all participants. Target gestures were comprised of primitive elements including hand shape and sequences of movements with one or both arms. Each participant's movements were videotaped for later analysis of movement kinematics.	Blocked (NR)	Total error Total Movement time			NR	ASD vs TD: more total errors	N	0.73 (Good)
Fukui et al. (2018)	Hand-eye coordination task Participants wore liquid-crystal shutter goggles and rested their hand on a pressure-sensitive switch button (a starting position). They required to reach out to grasp the target object at a comfortable daily life speed and then lift the object about 5 cm. After lifting up the object, the participant put the object	Blocked (15 trials per condition)	Total movement time	Reaction Time Difference Between the Grasp-End Time and the Time of Lifting	Peak Wrist velocity Normalized Jerk Score Peak Grip Aperture (PGA)	NR	ASD vs TD: has smaller PGA than TD more DiffGrLf	N	0.77 (Good)

	back to where it had been and returned his/her hand to the starting position.			Initiation (DiffGrLf)	Time to Peak Grip Aperture				
Kostrubiec et al (2018)	Hand-eye coordination task The child had to move a green circle left–right on a computer screen by oscillating a slider with his/her index. The finger motions were recorded by for further analysis by a data acquisition chain transforming the angular position of the slider into voltage by a linear potentiometer. Four experimental conditions were administered sequentially: (1) spontaneous oscillation, (2) spontaneous coordination, (3) 0° intentional coordination and (4) 180° intentional coordination.	Blocked (5 trials per condition)	AE* RP* variability Apen* Cross corr*		The Kinematics of Oscillation Period and Amplitude	NR	ASD VS TD: higher AE and RP lower apen and cross corr in spontaneous coordination	N	0.81 (Strong)
Zheng (2015)	Upper limb movement task Participants were asked to performed a computer task that a green light located between the start position and the smaller target served as a visual ready signal. Once the green light was turned on participants were aware that a target would soon appear. They were asked to move as fast and as accurately as they could.	Blocked (30 trials per condition)	Total movement time Constant error Variable error	Premotor reaction time Motor reaction time	PA PV PD TPV Time after PV Spatial Variability at kinematic markers	NR	ASD VS TD: longer total movement time in 3D condition; shorter total movement time in 1D condition; less consistent on spatial variability at kinematic landmarks	N	0.69 (Moderate)
Glazebrook et al (2006)	Upper limb movement tasks Participants were instructed to place their index finger/banjo pick on the start location, after which the experimenter initiated a random fore period of 2000–2550ms. Next, either the right or left circle turned red and the program initiated an OPTOTRAK recording. The red circle was also the signal for participants to move their index finger as quickly and accurately as they could to the target circle.	Blocked (240 trials)	Total movement time	Reaction Time	PA Displacement at PA PV TPV TPA Proportional time after PV Displacement at PV	NR	ASD vs TD: longer total movement time longer reaction time lower PA more variable of the displacement at PA lower PV longer TPV	N	0.73 (Good)
Linkenauger et al (2012)	Reach and grasp task For the reachability task, the experimenter moved a white chip from the opposite side of the table toward the participants or away from a point directly in front of the participant to the opposite side of the table. Participants made reachability	Random (NS)	Total error			NR	ASD VS TD: more total error than TD	N	0.69 (Moderate)

	estimates when the chip was moving toward or away from one of three locations—central, contralateral and ipsilateral. For the grasp ability task, participants were presented with each of the blocks one at a time in random order. Participants were told to anticipate whether they could grasp the block in a way to place their thumb on the black line on one edge of the block and then extending their hand across the entire block to place any one of their other fingers on the black line on the other side of the block.								
Stoit et al (2013)	Reach to grasp task Participants were seated behind a table facing a 17 inch LCD monitor (75 Hz; 1,024 by 768 pixels) at a distance of approximately 80 cm. Immediately in front of and aligned to the midline of the participant a response box was positioned that served as a starting position for the subject's hand in each trial. Both manipulanda had the same shape, but their vertical orientation was reversed. One manipulandum was presented with a small cylinder on top (r = 0.80 cm, height = 1.80 cm) affording a precision grip and requiring an approach trajectory from above (see Fig. 1). The other manipulandum was presented with the large cylinder on top (r = 3 cm, height 8 cm) affording a power grip and requiring an approach trajectory from the side.	Variable (12 trials per condition)	Total movement time Total error	Reaction time		NR	ASD vs TD: slower total movement time	Y NR	0.77 (Good)
Rinehart et al (2006a)	Upper limb movement tasks The basic task involved the movement of a non-inking stylus from the center start position toward either a left or right target in response to the illumination of the left or right LED.	Blocked (32 trials per condition)	Total movement time	Reaction time		NR	ASD vs TD: longer reaction time	N	0.73 (Good)
Brezis et al (2017)	Combine tasks (imitation and reaching task) The Mirror Game Procedure(imitation): Players faced each other holding handles which can move along parallel tracks. Players were told that this is a collaborative game whose purpose is to "create movements together like a conversation of movements. In the first round, the participant led (Leading round), in the second the participant followed the experimenter's lead (Following round), and in the third round the two players created motions together, "with no leader or follower" (JI round). In the Reaching task:	Blocked (NR)	Total movement time of the imitation task Total error of the reaching task		Motion velocity of the imitation task	NR	ASD vs TD: lower motion velocity than TD.	N	0.81 (High)

	Participants viewed 15 static images of the red handle in six different positions displayed for 4 s at a time, and were instructed to “move your handle across from the red handle’s position as fast and as accurately as you can using your dominant hand.								
Hayes et al (2018)	Upper limb movement tasks All participants performed a familiarization period, a practice-phase, a retention test, and a perception task. The participant was informed that a trial would begin with three red target circles being presented horizontally across the midline of the monitor. To physically start a trial, the participant was informed that they should move the stylus so that the white cursor was positioned within the left-hand start target. Once positioned, the three targets turned green, and a trial could be commenced. The sequence was to move the cursor to hit the centre target (segment 1), followed by a reversal movement back to the start target (segment 2), and finally a reversal so that the cursor moved back through the centre target to stop in the end target on the right-hand side of the display (segment 3) to exactly attain the timing goal of 1700 ms. To ensure a participant engaged in sensorimotor learning, he/she was informed that knowledge-of-results would be displayed on the monitor after each trial attempt (e.g., Too Fast or Too Slow by 98 ms).	Blocked (30 atrials)	Total error			ASD_pre VS ASD_post:less total error	ASD vs TD: more total error	Y ASD vs TD: more total error	0.81 (High)
Foster (2019)	Combine tasks (observational practice and imitation) Participants observed two different (typical and atypical velocity profiles). To create the models, a human volunteer practised performing the two aiming movements using the hand-held stylus on a graphics tablet in order to control a white-dot presented on the screen, which represented the stylus cursor, from the home position to the end positioning order to exactly achieve the criterion movement time of 1700 ms.	Blocked (30 trials)	Temporal constant error Temporal variable error		PV Mean tPHV	ASD_pre VS ASD_post:PV occurred earlier for the imitation task.	ASD vs TD: more temporal variable error in the observational practice task.	N	0.81 (High)
Diaz (2020)	Hand-eye coordination tasks Participants were instructed to flex and extend the right lever in the horizontal plane in order to move a cursor in and out of two clearly defined target areas. The participants were instructed to complete this task as quickly and accurately as they could.	Blocked (60 trials)	Total movement time Movement time	Dwell time	PV %TPV	Non sig	Non sig	Y Non sig	0.65 (Moderate)

Glazebrook et al (2009)	Hand-eye coordination tasks Participants were seated comfortably so that the home position was centred with their midline. They wore an eye tracker that recorded eye movements at 60 Hz. A rigid body with four infrared emitting diodes was attached to the eye tracker to allow free head movement. A banjo pick with one infrared emitting diode (IRED) attached was placed on the participant's dominant index finger. The purpose of using blocked trials was to create a situation where participants could fixate the target and therefore only needed to prepare and initiate a hand movement to reach the target.	Blocked (80 trials)	Total movement time	Reaction time	Spatial variability at each of the kinematic markers (PA, PV, PD & End point) TPA TPV	NR	ASD vs TD: longer total movement time; longer reaction time and more variability; more spatial variability; longer TPA & TPV	N	0.81 (High)
Campione et al (2016)	Reach and grasp tasks At the beginning of each trial, the experimenter helped the child to place his/her right hand on a fixed starting position, with the thumb and the index finger in a relaxed pinch position. When the child was ready to perform the task, the experimenter gave him/her the signal for reaching and grasping the object by saying "Grasp it!" Children were instructed to reach for, grasp (Fig. 1), and lift the object vertically. Then, they placed the object back in its original location.	Blocked (16 trials)	Total movement time for reaching Total movement time for grasping Grasp finger closing time	Reach deceleration time % deceleration time	Reach arm PV Reach time to arm PV Reach arm PA Reach time to arm PA Reach arm PD Reach time to arm PD	NR	ASD vs TD: longer total movement time for reaching longer reach time to arm PV; longer reach time to arm PD	N	0.81 (High)
Van Swieten et al (2010)	Grip Selection task The participants" task was to reach and grasp the dowelling with a pincer grip following the appearance of the white arrow, and then rotate it to an indicated final location. The dowelling started with the thumb (red) end in one of two different positions separated by 90°.This end was to be rotated 180° either clockwise or anticlockwise, with the thumb following the white arrow (thus there were four possible trial configurations). On each trial, participants reached out and grasped the object as fast as possible, then turned it. They were asked to hold their final postureuntil the stimulus disappeared.	Blocked (32 trials)		Minimal rotation grip force		NR	Nonsig	N	0.58 (Moderate)
Gidley Larson et al (2008)	Reaching task Participants were positioned in front of a horizontal screen. Using their right hand, they grasped the	Blocked (150 trials)	Total error			ASD_pre VS ASD_post:less total error	Non sig	N	0.77 (Good)

	handle of a robot tool that was positioned below the screen. Participants were instructed to move the cursor to the target. The behaviour of the robotic tool underwent two different kinds of changes and we considered the ability of the subjects to adapt to these changes. In one block of trials, the robot's dynamics changed as it produced a force field. In another block of trials, the robot's kinematics changed as it imposed a rotation on the position of the cursor with respect to the position of the handle.								
Parma et al (2014)	Reach and grasp task The child and the model sat at a table facing each other and the object (i.e., a glass) was located in the center aligned with both body midlines. The child and the model rested their right hand on a starting pad, located at a 20-cm distance from the object, gently opposing the index finger and the thumb (Starting position). Before each trial started, both the child and the model smelled the pad on the object, sensing the maternal odor, the odor of another mother or no odor. At the sound of the first auditory cue, the model could either naturally reach and grasp the object, allowing the child to observe the action or remain still, preventing the child from the observation of a reach-to-grasp movement (Observation of model's movement).	Blocked (30 trials per condition)		Reaction time	tPHV	NR	ASD vs TD: longer reaction time	N	0.77 (Good)
Cavallo et al (2021)	Reach and grasp tasks Children were asked to reach for and grasp the bottle to complete three sequential manipulation tasks: place the bottle into a box (grasp-to-place), pour some water into a glass (grasp-to-pour), or pass the bottle to a co-actor (grasp-to-pass), who would then either place the bottle into the box or pour some water. In each trial, children were asked to perform at a natural speed after an auditory tone. The child's right hand was outfitted with 8 retro-reflective hemispheric markers (6.5 mm in diameter) placed on the metacarpal joint and the tip of the index and the little finger, the trapezium bone of the thumb, the radial aspect of the wrist and the centre of the hand dorsum.	Blocked (12 trials per condition)	Total error Wrist height	Wrist jerk Grip Aperture	Wrist Velocity Wrist acceleration	NR	ASD vs TD: more total error	N	0.77 (Good)
Pierno et al (2008)	Reach and grasp tasks Two participants, a model and an observer, were seated facing each other at a table. A 'go' signal given by the experimenter indicated to the human	Blocked (20 trials)	Total movement time	Time of maximum grip aperture	TPV	NR	Nonsig	N	0.77 (Good)

	model to perform a reach-to-grasp action towards the target stimulus. The stimulus was a plastic sphere (diameter: 5 cm) positioned at a distance of 20 cm from the hand starting position along the subjects' mid-sagittal plane. As soon as the action was completed and the hand of the model returned to the starting switch a sound was presented.The sound indicated to the observer, either a normally developing or autistic child, to perform a reach-to-grasp action towards the target stimulus. Participants were not explicitly instructed to imitate the previously observed action but were simply asked to perform a reach-to-grasp action towards the target stimulus when the sound was presented.								
Yang et al (2014)	Reach and grasp tasks Qualisys motion capture system was used to recorded reach-to-grasp movement by five infrared light emitting diodes cameras to capture the light reflected from three passive markers (diameter: 1 cm) placed on the testing hand (preferred hand). One of the three markers was placed on lateral styloid process of the wrist to record reaching component, and another two were placed on the nails of thumb and index finger to record grasping component.	Variable (20 trials)	Total movement time Movement unit NJS*	MGA* NMGA* PTMGA*	PV PTPV	NR	ASD vs TD: longer movement time when grasping small target; more movement units; larger NJS in no visual and visual small conditions. larger MGA in visual feedback condition; larger NMGAin the visual feedback condition.	N	0.58 (Moderate)
Nor et al (2016)	Gait Two electrodes have been used to capture EMG signals from Biceps Femoris (BF) and Rectus Femoris (RF) muscles of ASD and TD children. All subjects were asked to walk without assistance in normal pace.	Blocked (NR)		Amplitude of EMG signals		NR	ASD vs TD: more amplitude of EMG signals	N	0.58 (Moderate)
Shafer (2019)	Hand-eye coordination task Participants used a wireless LED computer mouse to control the onscreen cursor during the sensorimotor task. Participants performed a stimulus-tracking task during which they controlled a cursor (green dot subtending a visual angle of	Variable (128 trials per condition)	Total error			NR	Non sig for total error	N	0.73 (Good)

	~0.3°) and followed a moving target (grey square subtending a visual angle of ~1°) that moved at a constant velocity of ~2°/second across the computer screen. Participants were instructed to continue moving the computer mouse as if the target and cursor were still visible. The target and cursor reappear at the end of the no visual feedback trials.							
Papadopoulos et al (2012)	Upper limb movement tasks Participants were instructed to draw 10 continuous sets of straight lines between the displayed targets without lifting the stylus from the touchscreen, aiming for the centre of the targets. Participants were instructed to draw lines between targets as fast as they could without compromising the accuracy demands of the task. Movements were performed with the participant's dominant hand.	Blocked (50 trials per condition)	Total movement time Constant error Variable error		NR	ASD vs TD: more constant error and variable error	N	0.77 (Good)
Sachse et al (2013)	Combine tasks (motor screening task; aiming task; reaction time task) The motor screening test (MOT) is a simple reaction speed task conceptualized to screen for vision, instruction comprehension and movement time. Participants are instructed to touch a cross appearing on the screen as fast as possible. In the aiming task, subjects are presented with a small and a big circle on two positions in random order. Participants have to touch the assigned circle as fast as possible. In the reaction time (RTI) task participants are instructed to touch a circle as soon as a smaller yellow stimulus appears inside this circle. During waiting for the stimulus participants press a key on a key pad. One and five choice conditions were presented.	Blocked for all tasks (NR)	Combine reaction time and total movement time		NR	ASD vs TD: longer combine reaction time (g=0.86) and total movement time (g=0.04) in the five choice reaction time task.	N	0.77 (Good)
Centelles et al (2013)	Upper Limb Movement tasks The aim of the control task was to determine whether the motor response time differed between the groups of children and whether they depended on the children's handedness. For this purpose, the children were asked to press a key on the	Blocked (8 trials per condition)	Total error	Reaction time	NR	ASD vs TD: more total error; longer reaction time	N	0.77 (Good)

	computer whenever a cross appeared on the screen. The response times were recorded during four sessions, each consisting of eight trials, and the use of the right and left hands was alternated between sessions.								
Gamez Corral et al (2017)	Upper limb movement tasks The system was fastened to a table with adjustable tracks to position the arms in a comfortable position matching the participant's limb structure. Participants were instructed to flex and extend the right lever in the horizontal plane and to move a cursor in and out of two clearly defined target areas on the screen in front of them. The participants were instructed to complete this task as quickly and accurately as they could.	Blocked (60 trials)	Total movement time	Dwell time	%TPV	NR	ASD vs TD: longer total movement time; longer dwell time	N	0.62 (Moderate)
Jiménez et al (2014)	Imitation task In the imitation task, participants were instructed to watch a series of actions performed by a model, and to "do as they see", right after the demonstration finished. To minimize the impact of social factors, the demonstrations were shown as 5-s video-clips which showed the torso, arms, and hands, but not the head, of an adult model, who was sitting in front of a metal pen holder and of a wooden bar resting horizontally on a pair of cradles. During the movie, the model grasped the bar from the cradle and inserted it into the metal pen holder. Analogous material was located in front of the observers, in a mirror arrangement with respect to the items shown in the movie. Participants were told that they should do as they see in the movie, as soon as the video ended and was replaced by a black screen displaying the sentence: "Your Turn." Imitation instructions remained deliberately vague as to exactly "what" should be imitated, in order to leave up to participants the final decision on what to imitate. Participants' hand movements were continuously video-taped, and their performance was encoded offline.	Variable (32 trials)	Proportion of trials in which imitated comfortable or non-comfortable end states Proportion of trials in which participants reproduced the modelled goal Mimicry score			NR	ASD vs TD: Less tendency to imitate in non-comfortable end state; less tendency to reach the goal	N	0.77 (Good)
Andrew (2016)	Imitation task Participants were provided with general instructions to "watch and then copy the movement displayed by a white dot on the computer monitor".	Blocked (30 trials per condition)	Timing error Variability score (Timing variability)		PV TPV	NR	ASD vs TD: higher variability score;	N	0.81 (Strong)

	To examine the imitation of biological motion, three non-human agent models were created that displayed typical, atypical or constant velocity profiles. To do so, the volunteer practised the task by performing typical goal-directed aiming movements using a hand-held stylus on a graphics tablet until a white dot/cursor (diameter = 6.25 mm), which represented the stylus, moved from the left-hand home-target to the right-hand end-target in 1700 ms.				lower PV		
Buard et al (2018)	Imitation task The stimuli consisted of a photorealistic animated right hand, presented in the third-person perspective (Figure 1). The index or pinky fingers from this hand were lifted briefly 3 s after the beginning of the video (1 s duration for entire movement, returning to rest) every 6 s. Subjects were asked to imitate the finger movement with their right index or pinky finger as seen on the screen. Index and pinky imitation stimuli were presented in randomized order to the subject using E-prime 2.0.	Blocked (80 trials per condition)	Total error Total response time Response rate	NR	ASD vs TD: lower response rate	N	0.77(Good)
Xavier et al (2018)	Imitation task The tightrope walker paradigm (Thirioux et al., 2009) is an experimental setup designed to test the ability to change spatial viewpoints i.e., own-body transformations, during a spontaneous motor imitation task. During 7 following trials, numbered from 1 to 7, the TW, walking successively either forward or backward, was alternatively shown in two orientations: (i) a front-facing orientation when the TW walks forward and a back-facing orientation when, the TW walking backward, Participants were instructed to observe the tilts of the TW and to lean when he was leaning. Participants were also asked not to walk even when the TW was walking and to stand still when he was.	Blocked (7 trials)	Total movement time Total error	NR	Nonsig.	N	0.73 (Good)
Gauthier et al (2018)	Imitation task The tightrope walker paradigm is an experimental setup designed in order to test the ability to change of spatial viewpoints in a spontaneous motor task. During self–other interaction, it enables one to test the ability to (1) inhibit one's ego-centered perspective and (2) adopt the visual- spatial perspective of others. The animated tightrope	Blocked (7 trials)	Number of tagged movements Latency Amplitude Length Overlength Overshoot	NR	ASD vs TD: less number of tagged movements and higher amplitude	N	0.81 (Strong)

	walker (TW) walking on a rope was displayed life-sized by a rear-projector onto a large screen. Before the movie started, we asked participants to find a comfortable position, legs slightly apart and not to shift from their position in response to the moves of the TW. For each participant, we checked the ability to understand the motor imitation task: the participant was asked to imitate the clinician who stood in front of him holding a wooden bar and tilting it on both sides.							
Poole et al (2018)	Imitation task Each trial began with a fixation cross, followed by a still image of a hand and a movie clip of a hand sequence. Participants imitated when the exclamation mark appeared. A video clip of the movement sequence was then played (3240 ms), followed by an exclamation mark coupled with a sound signal (beep, 1000 ms) signalling to the participants that they should imitate the movement.	Blocked (4 trials per condition)	Total error		NR	Non sig	N	0.77 (Good)
Taheri-Torbati et al (2019)	Imitation task Participants stood three metres away from the centre of the goal that was in front of them and had to throw the bean bag at the centre of the goal. The reason for this assignment is that it is a standard measurable way for assessing and it was new for children. The aim of the researchers was to achieve a selected task which is safe and rather uncommon, and can be learnt in a relatively short period of time in children with ASD. The primary objective of both groups was to imitate the pattern of model. The observed model involved throwing a bean bag towards the target while the participants watched and the coach instructed the participants to pay attention to the direction of the model. Before and after each training block, the participants observed five performances of model. The LM group observed the model in live performance, while the VM group watched the model performance on a laptop screen. Also, a break of five minutes was allotted after each block. After performing the training sessions, participants also participated in post-test and a long-term retention (with one-week interval).	Blocked (not specific -17 blocks)	NoRMS (variability of intralimb co-ordination) NoRMD (normalised root mean difference)		ASD_pre vs ASD_post: decreased NoRMS improved NoRMD	Nonsig	Y Non sig for all	0.77 (Good)

Gowen et al (2020)	Imitation task Each trial started with a white fixation cross that flashed green (2000 ms), followed by a still image of the hand in the start position of the movement sequence that was displayed for 2000 ms, allowing the participant to move their hand to the equivalent start location on the table. A video clip of the movement sequence was then played (3240 ms), followed by an exclamation mark coupled with a sound signal (beep, 1000 ms) signalling to the participants that they should imitate the movement. The experiment was split into two blocks. Participants first completed a 'general instruction' block with the following instruction presented on the screen and read to them: 'Watch the video clip carefully and then copy what you saw as best you can'.	Variable (24 trials per condition)		Horizontal amplitude Vertical amplitude	PV	NR	ASD vs TD: smaller vertical amplitude	N	0.81 (Strong)
Vabalas et al (2020)	Imitation task During the experiment, all participants were asked to imitate sequences of simple hand movements. Participants first watched then imitated a video shown on a screen while their eye and hand movements were recorded using an eye tracker and a motion tracker. Movement sequences were simple and consisted of two point-to-point movements between three out of four possible locations 15 cm apart on a horizontal straight line.	Variable (NR)	Total error		PA PD TPA TPD	NR	ASD vs TD: earlier PA and later PD	N	0.81 (Strong)
Radonovich et al (2013)	Postural control task Postural control was assessed while participants stood quietly on a forceplate (Type 4060–10, Bertec Corp., Columbus, OH) embedded level to the floor. Subjects were instructed to stand as still as possible, with their arms at their side.	Blocked (4 trials)		GRF* COP_ML & COP_AP The sway area (peak displacements in ML and AP)		NR	ASD vs TD: greater sway area	N	0.77 (Good)
Wang et al (2016)	Postural control task Prior to testing, each participant's postural limitation boundary was determined based on the maximum extent to which he/she could lean in each of four directions: forward, backward, leftward, and rightward. Participants then were guided through the postural limitation trials by the examiner, who used the following instructions: "For the next part, you will lean your body as far as possible without raising your feet from the ground. Now, slowly lean your body forward, hold, come	Blocked (10 trials- 3 conditions and one postural limitation boundary trial)		the standard deviation of COP_AP & COP_ML COP trajectory length		NR	ASD vs TD: has increase COP standard deviation; greater COP trajectory length	N	0.77 (Good)

	back to the center. Slowly lean your body backward, hold, etc." for each of the directions. Each individual's postural limitation boundary then was modeled as an ellipse based on the individual's COP maximum for each direction as well as the force platform coordinates.							
Ardalan et al (2019)	Postural control task Because previous work has demonstrated balance improvements in ASD as a function of this training, training sessions 2–4 (of 18) were used in these analyses to characterize motor skills before the majority of the improvements due to training but after the initial intake assessment. While postural sway and peripheral-limb movements were commonly found to be informative for the classification, the results suggested that no single motor domain was able to reliably distinguish between the two groups. In other words, combined information about movement across the body was necessary for the accurate classification.	Blocked (NR)	Precision accuracy Recall accuracy Specificity accuracy		NR	NR	N	0.73 (Good)
Conrad-Forrest et al (2020)	Postural control (hopping task) Participants were asked which was their preferred kicking leg, asked to step onto a step with the leg they chose recorded, and a push test was completed to see which leg they would catch themselves with. The leg that was chosen for at least two out of the three methods was determined to be the participant's dominant leg. Reflective markers were placed on specific bony landmarks based on a modified Cleveland marker set. Tracking markers were placed to track motion of each body segment (head, trunk, upper arms, lower arms, hands, pelvis, thighs, shanks, and feet). Calibration markers were also placed to identify segment endpoints and joint centres. All data were captured using Cortex Motion Capture software. While the participant was on a force plate, a standing calibration trial was used to derive the local coordinate systems and segment endpoints.	Blocked (5 trials)		Pelvis ROM* Hip flexion Hip adduction Hip internal rotation Knee abduction Knee flexion Ankle dorsiflexion	NR	Nonsig	N	
Bojanek et al (2020)	Postural control task Participants completed three postural control tasks using one AMTI force platform and one stepping task using two adjacent AMTI force platforms. During the neutral stance, participants stood as still	Blocked (3 trials per condition)		COP variability COP trajectory length	ASD_pre vs ASD_post:increased COP trajectory length across stance condition;	ASD vs TD: more COP trajectory length;	N	0.73 (Good)

	as possible with their feet shoulder width apart and their arms resting at their side. During the test of circular sway, participants stood with their feet hip width apart and made a circle with their body at a natural speed. Participants completed trials in which they took one step forward from one force platform to an adjacent force platform.			COP duration COP velocity MI* during circular sway Amplitude and duration of APA*	reduced MI during circular sway across stance condition.	less MI during circular sway; less COP duration; more COP velocity;		
Stewart et al (2013)	Imitation task The video showed an actor as he drew shapes freehand on a laptop identical to laptop A. In the [object movement reenactment (OMR)] condition, the video showed the same actor watching a black dot moving on a white background on the tablet screen. Each video clip was shown to the participant on laptop B, following written instructions asking them to pay attention to the shape, size, and speed of the stimuli. This aspect of the task was further emphasized with additional verbal instructions to the participant to carefully watch and copy the shape, size, and speed of the stimuli. After each clip, laptop B prompted the participant to reproduce the movements they had watched, with the written cue “Now you do it.” The participant then drew his response on laptop A's screen.	Blocked (27 trials per condition)	Total error of path length Total error of action duration		NR	ASD vs TD: more total error of path length	N	0.69 (Moderate)
Bird et al (2007)	Imitation task All stimuli were presented on a screen in colour on a black background. Each imperative stimulus was a photograph of a human or a robotic hand in an opened or a closed posture. It was preceded by a warning stimulus representing a neutral posture of the same hand type (human or robotic). The participant's right forearm lay in a horizontal position. It was supported by an armrest which allowed the hand to move. The fingers moved upwards during opening responses and downwards when closing. After each response, participants returned their hand to a neutral starting position. In each block, participants were instructed to make a prespecified response (open or close) as soon as possible after the movement stimulus appeared. Participants were instructed to refrain from moving their hand in catch trials, when the imperative stimulus was not presented.	Variable (12 trials per condition)		Mean reaction time on compatible and incompatible trials	NR	Non sig	N	0.89 (Strong)

Travers (2011)	Postural control task In this task, participants stood on a Nintendo ® Wii balance board that collected data via Bluetooth connectivity on a nearby laptop. Prior to the motor tasks, the balance board was calibrated for each participant (by having them hop on and off the board), and the laptop was able to record the participant‘s center of balance (left versus right foot) and stability over time with a data point for every 2.5 ms.	Random (6 trials)	Total movement time of balance Distance from centre of balance in each pose The variability of balance over time		NR	ASD vs TD: shorter total movement time of balance	N	0.73 (Good)
Chen et al (2019)	Catching task The child was asked to catch a foam ball rolling down from a stationary ramp was used in this study. The catchong paradigm not only controlled for inherent variability associated with throwing and catching, but also removed social components often inherent in catching task. For each catching trial, the child first stood quietly with 2 hands aside the thighs, followed by 1 experimenter dropping a foam ball from the top of the ramp. The child was instructed to catch the ball with 2 hands in the catching zone.	Variable (15 trials per condition)	Total error Total movement time	APA Initiation time of arm movements and COP COP displacement	NR	ASD vs TD: more total error; lower APA; occurs earlier initiation time of arm movements and COP;	N	0.77 (Good)
Forbes et al (2016)	Imitation task (auditory-motor interaction) Participants were told that they would be playing a game with two avatars but would first practice the game with another avatar. Participants were told that the avatars’ movements were based on the movements of people that had previously been in the lab. In the practice session with Mike, participants were told that they would hear a ‘dong’ sound which was the avatar’s cue to move. The avatar would then point to three of the targets in front of them before returning to their resting position. A ‘ding’ sound then occurred after a variable delay (1200–1800 ms). This sound acted as the participants’ cue to move and they were instructed to point to the same targets that the avatar moved to.	Serial (64-16 combinations repeated four times)	Total error		NR	Non sig	N	0.73 (Good)
Hallett et al (1993)	Gait Gait was analyzed by a bilateral sagittal plane technique. Ki¬ nematic data were sampled within a stationary orthogonal laboratory coordinate system defined by a vertically oriented axis and ay axis	Blocked (3-7 trials)		cadence step length step width step length symmetry	NR	ASD vs TD: different in ankle range of motion (NS for p value).	N	0.58 (Adequate)

	parallel to the path of progression. was defined by using 20 spherical retroreflective targets. The subjects, dressed in shorts, walked with bare feet at a self-determined pace. Data acquisition began approximately 1 second before the subject entered the calibrated volume, and it ended approximately 1 second after the subject left the volume.			step width symmetry stance time stride length average gait velocity knee joint angle knee joint moments ankle joint moments Ankle range of motion				
Vernazza-Martin et al (2005)	Gait The children wore a bodysuit on which fifteen spherical retroflective markers (15 mm in diameter) were taped in pairs on the children's back as follows: fifth metatarsal joint (markers 14 and 15), external malleolus (markers 12 and 13), tibial plate (markers 10 and 11), trochanter (markers 8 and 9), iliac spine (markers 6 and 7), acromion (markers 4 and 5), mastoid (markers 2 and 3); one marker was fixed at the posterior fontanel level. The children walked between two beams delimiting the access path to the playhouse. The two ELITE system cameras positioned behind the children recorded the infrared reflection of the spherical retroflective markers while a video camera positioned behind the children recorded the scene. Recordings of the healthy children and the autistic children were performed in different sessions.	Blocked (TD: 7 trials; ASD: 4-14 trials)	Stride duration; step length; swing and stance periods	cadence; Head and shoulder angle Angular Dispersion of Head, shoulder and Pelvis; Angular Dispersion of Head and Trunk The anchoring index of the head, shoulders and pelvis in the frontal plane	gait velocity;	NR	ASD vs TD: smaller step length; greater head and shoulder angle in the frontal plane; greater angular aspersion of head, shoulder in horizontal plane ; greater angular aspersion of head and trunk than TD in the sagittal plane.	N	0.58 (Adequate)
Rinehart et al (2006b)	Gait Clinical Stride Analyzer (CSA; B & L Engineering, CA, USA) was used to gather data pertaining to average gait measurements over a 10m walk for each individual trial. CSA involves placing an electronic footswitch in each shoe (i.e., under the sole of the participant's feet), which in turn is connected to a data recording device that is strapped to the waist. Each footswitch has an electronic sensor under the heel, toe, 1st, and 5th metatarsals. Pressure on these areas activates the	Variable (5 trials per condition)	CoV* in stride length	CoV in: cadence double support (time of both feet are grounded in a gait cycle)	CoV in velocity	NR	ASD vs TD: higher CoV in stride length	N	0.73 (Good)

	sensor, and informs the data recording box. A light sensor, also connected to the recording device, is attached to the participant's upper arm. This sensor is scanned by a light at the beginning of the 10-m walkway (thus activating the box and data collection); similarly, a light at the end of the walkway informs the box to cease recording. After each walk, the data recording box is connected to an IBM compatible computer, and this data is downloaded into a printable text format. Average data are produced for each individual walk.								
Rinehart et al (2006c)	Gait Participants walked along the length of the GAITRite walkway. Participants completed five trials of preferred gait followed by tandem walking. Participants walked using their preferred (normal) gait and were instructed to 'walk to the line at the end of the mat, keeping in the middle as you go' and told to 'keep in the middle of the pink mat'. A white strip of elastic (width 20mm) was placed along the centre of the mat, from beginning to end. Participants were instructed to walk along the line, placing one foot in front of the other.	Blocked (5 trials of preferred gait, NS of Tandem walking)	stride length	cadence double support Heel-to-heel base of support CoV	Velocity	NR	ASD vs TD: more variable for stride time and length	N	0.88 (Strong)
Dufek et al (2017)	Gait Participants were instructed to stand in a "T" pose for a static calibration trial that was used to establish zero degrees of joint flexion. Participants were instructed to perform 20 walking trials at a self-selected pace. Participants were instructed to walk as normally as possible, and were reminded to do so when necessary.	Blocked (20 trials)		vGRF AP GRF Sagittal plane hip, knee, and ankle joint		NR	ASD vs TD: less consistency in joint angles.	N	0.69 (Good)
Biffi et al (2018)	Gait The participants were instructed to walk at their own natural speed for 6 min in the mediolateral middle of the treadmill, placing one foot on each separate belt. During this habituation period, the speed of the belts was real-time adjusted to meet each child's time-varying walking pace. After this 6-min period of adaptation, a 20-step trial was recorded as baseline (T0). Subsequently, each participant was exposed to 20 trials with a discrete gait perturbation: after a random number of steps, a single perturbation was applied to the dominant side at toe-off, using a split-belt acceleration. Single steps around perturbations (before, during, and after) were recorded. Finally, at the end of the	Blocked (20 trails as main task, 20 trial 20 steps as retention)	The walking speed	the peak of ankle flexion moment the peak of knee extension the hip flexion at IC* the ROM* of ankle flexion the pelvic tilt at IC the mean pelvic tilt		ASD_pre vs ASD_post: different in the speed, the peak of ankle flexion moment, the peak of knee extension and the hip flexion at IC. (NS for higher or lower); significantly different in the ROM of ankle flexion, the	ASD vs TD: lower peak of knee extension	Y NR	0.77 (Good)

	perturbed trials, we recorded 20 steps as a post-perturbation trial (T1).					pelvic tilt at IC and the mean pelvic tilt			
Chen (2020)	Gait Upon arriving the laboratory, each participant's body parameters were measured, including height, weight, and bilateral trochanteric heights, leg lengths, knee widths and ankle widths. Basedline: Participants then completed a 10 m over-ground walking test during which they were asked to 'walk as usual'. Experiment: 'V-Gait 'treadmill, consisting of a warm-up trial followed by four test conditions. Participants were instructed to 'watch the road in front of you. Try to remain stable as you walk.'.	Random (5 trials)	Total movement time	Walking speed Step time Step length		Nonsig	Nonsig	N	0.58(Adequate)
Zakaria et al (2020)	Gait During data acquisition and experimental set-up, a depth camera is used as a motion sensing input device for the proposed markerless-based gait technique. This sensor provides the coordination of 20 primary body points. For the walking task, subjects are advised to walk freely bare footed with their comfortable speed to keep the nature in their walking behavior and without any assistant or walking aid.	Blocked (10 trials)	Total error			NR	NR	N	0.5 (Adequate)
Hasan et al (2017)	Gait After static calibration, participants were instructed to perform a straight barefoot walking along the walkway at their self-selected speed. Participants were allowed to perform several practice trials for familiarisation and then an average of five to ten walking trials were recorded from each participant. However, several ASD participants with small stride length and sensory issues had to perform more than twenty trials in order to achieve a valid walking trial with a single foot contact on each force plate.	Blocked (5-10 trials)	Total error		Error rate on kinematic and kinetic gait features	Non sig	Non sig	N	0.58 (Adequate)
Eggleston et al (2017)	Gait The instructions were to start with feet approximately shoulder-width apart and squat to their preferred depth and pace. Following the pre-test, participants underwent live animation biofeedback training. During training, participants watched a skeletal model performing squats in real-time, during the training period. Participants could also see their own skeletal model simultaneously. The training trials consisted of five	Blocked (50 trials)		Angular joint positions Ascent and decent velocities		Nonsig	Nonsig	N	0.73 (Good)

	blocks of ten trials, with two-minute rest periods between trial blocks, resulting in fifty training trials. At the post-test, similar to the pre-test, we instructed participants to perform eight squats, with brief rest periods between each squat.								
Stevenson et al (2015)	Combined task: Gait and Upper limb movement tasks The Timed Up and Go (TUG) test is a commonly used test of motor control and was used to measure timing of initiation of movement and functional motor control in the sample. Gait Parameters: Walking data were collected during four conditions: walking at a self-selected velocity (SSV) without added distractions, walking while dual tasking, walking over an obstacle that was visible in advance of beginning to walk (feed-forward), and walking over an obstacle that appeared after beginning to walk (feedback control). All trials were Vompleted by walking over the GAITRite® while being instrumented with the Mobility Lab™ sensors attached as previously described.	Variable (4 trials per condition)	Total movement time for TUG task	Symmetry CoV		NR	Non sig	N	0.62 (adequate)
Fulceri et al (2018)	Combined task (Reaching and interactive movement task) Children entered in the lab room at least 15 min before the experiment started, in order to familiarize with the lab environment. The experimenter entertained the child making sure to provide him/her with all information about the goal of the game-like experimental task (i.e. to help the experimenter to feed a monkey with bananas). In this time interval, a minimally obtrusive, wearable magneto-inertial sensor was fixed through a support on both child and experimenter right wrists (see 2.3 Section for the sensor description).	Blocked (151 trials – two tests)	Total Movement time Total error Asynchrony of reaching	Reaction time CoV of reaction time	PA TPA	NR	ASD vs TD: longer total movement time more total error greater asynchrony of reaching higher CoV of reaction time	N	0.73 (Good)
Zhao et al (2018)	Combined task (Reaching and griping tasks) In the adaptive practice session, each participant first completed eight Path Tasks (T1–T8) without path cues. The maximum score possible for completing a task without errors was 60 points, where participants achieved 30 points for reaching the right-hand targets and the other 30 points for reaching the left-hand targets, and they lost 1 point every time they hit the wall. The system recorded the scores and computed the average scores for these eight tasks to decide if	Blocked (NS- 64 practice trials)	Total error Task score Task efficiency	Movement speed CoV of speed Fin* Fout* CVin* CVout*		ASD_pre vs ASD_post:less variation of speed; more efficiency and greater level of improvement. increased grip force inside path.	NS	N	0.58 (Adequate)

	the participant should attempt more tasks and, if so, which kinds of tasks should be repeated.								
Fournier et al (2010)	Combined task (postural control and gait initiation) Children were asked to stand as still as possible for 20 sec with their arms comfortably at their side and facing a bare laboratory wall. The testing area was clutter-free, had a homogenous floor and was isolated from outside distractions with the use of monochromatic curtains. Children performed four trials. Trials where voluntary movements were observed were rejected and additional trials were performed. During GI trials, children stood with one foot on each force plate and upon hearing a verbal "ready" signal, were asked to take a short pause (1–2 sec) and then start walking to the end of a 4-meter walkway. The stepping foot and walking speed were self–selected. Children were allowed several practice trials to ensure comprehension of the task. Data from four trials were collected.	Blocked (2 trials per condition)		COPml, COPap & COP sway COP-COM max_ML COP-COM max_AP COP-COM max_resultant direction		NR	ASD vs TD: greater COPml, COPap & COP sway, COP-COM max_AP and COP-COM max_resulttant; displaced their COP less (towards the swing leg during gait initiation)	N	0.65 (Good)
Weiss et al (2013)	Gait For each individual trial, the participant walked along the length of the GR walkway. Participants completed six trials of preferred gait consecutively with about 30–60 s between each trial. Prior to the first trial, participants were given a demonstration and were then required to show their understanding of the instructions by walking down the mat. The participants were simply directed to walk to a research assistant who was standing approximately 2 m beyond the end of the GR mat. No participant required more than one demonstration and practice trial.	Blocked (6 trials)	Step length left/right Stride length left/right Cycle time Step time %swing time Stance time	Cadence (steps/min)	Velocity	NR	ASD vs TD: longer step length; longer stride length; less cadence, velocity, gait cycle time and % swing time; longer step and stance time;	N	0.69 (Good)
Fournier (2008)	Combined task (postural control and gait) Static Balance (Quiet Stance) All participants were asked to stand with their feet comfortably apart with one foot on each of the adjacent forceplates with a self–selected stance width. Foot positioning was marked on the initial trial and used for all subsequent trials. Participants were asked to stand as still as possible for 20 seconds with their arms comfortably at their side. Participants performed four experimental trials. Trials where voluntary movements were observed were rejected and additional trials were performed.	Blocked (4 trials per conditions)		COPml COPap COP sway COP–COMmax moment arms during quiet stance		NR	ASD vs TD: greater COPml, COPap, COPsway, and COP–COMmax moment arms during quiet stance	N	0.69 (Good)

	Dynamic Balance (Gait Initiation) Participants were asked to stand on the adjacent forceplates as previously described. Participants began from a quiet stance position, and were given a verbal cue to initiate movement. Once the cue was given, participants were asked to take a short pause (approximately 2 sec) and then start walking with their preferred foot, at a self–selected speed, in the forward direction. Data collection began with the verbal cue and continued for several steps after both feet had left the force plates. Participants were allowed several practice trials and data from 4 experimental trials were collected and used in subsequent analyses.						
Chen and Tsai (2016)	Combined task (force production and postural control tasks) Participants stood on a Kistler force platform that collected data for COP sway with a sampling rate set at 100 Hz. In addition, participants were asked to touch a customized 5 cm × 5 cm force plate that measured data for touch force in the vertical direction at a sampling rate of 1000 Hz. All participants received three trials for each of the four conditions: (1) EO(eyes open) + NT(no touch), (2) EO + LT(light touch), (3) EC(eyes closed) + NT, and (4) EC + LT	Blocked (3 trials per condition)		Touch force Magnitude of postural sway in AP* and ML* direction COP sway	NR	ASD vs TD: larger ML sway; greater COP sway without visual feedback.	N	0.77 (Good)
Travers et al (2017)	Combined task (finger tapping and Grip tasks) Grip: Grip strength was measured with a hand dynamometer according to the Halstead-Reitan Battery guidelines. Grip strength from the dynamometer was recorded and reported in kilograms (as is the industry standard). Participants were instructed to hold the upper part of the dynamometer in the palm of the hand and squeeze the stirrup with the fingers as tightly as possible. Finger tapping: Participants were instructed to tap the pointer finger as many times as possible until the experimenter with the stopwatch said stop. The majority of participants completed the task on the manual finger tapping board, but the younger participants completed the task using the electronic finger tapping version.	Blocked (2 trials-Grip; 3-7 trials – Finger tapping)	Finger tapping speed Grip strength		NR	ASD vs TD: slower speed and weaker grip strength	N	0.77 (Good)
Lidstone et al (2020)	Combined task (postural control and hand-eye coordination task)	Blocked (3 trials per conditions)	Hop Height	Hopping Frequency	NR	ASD vs TD: greater hopping frequency,	N	0.62 (Good)

	The two-legged hopping task was demonstrated by the experimenter standing in front of the child, however, the children were not given any instructions on how high to hop (Moran et al. 2013). To reduce the influence of aberrant arm movements during the hopping task, the children performed the hopping task with their arms folded across their chest (Figure 1). A retro-reflective marker was affixed to the sacrum using double-sided and Cover-Roll Stretch® tape. Participants were then positioned so they were standing on both force plates. The force plates were 1.5 meters from a television (55 in LED display, 3840×2160 resolution, 120 Hz refresh rate, Polaroid, MN, USA) monitor that was mounted on a height-adjustable TV stand.			Hopping Frequency variability Negative Sacrum Displacement variability			greater hopping frequency variability, negative sacrum displacement variability		
Johnson et al (2015)	Handwriting task Participants were given the instructions “I want you to write four cursive letter l's between these two lines. I want you to try to make your l's touch the lines, but not be any bigger or smaller than the lines.” Participants practiced five trials of each condition using pen and paper to ensure they understood the task, then the task was recorded on a digitizing tablet and stylus.	Blocked (NS- 5 practice trials for each condition-2 conditions)	CoV for stroke height, width, trajectory, duration	Stroke Dynamics: stroke duration an index of ballisticity Stroke Metrics: stoke height and width, and trajectory	Velocity CoV of velocity	NR	ASD vs TD: faster and have more ballistic on 40 mm.		0.73 (Good)
Grace et al (2017)	Handwriting task Handwriting movements were recorded using a back-lit, touch-screen, WACOM CINTIQ 12 inch graphics tablet with non-inking stylus, controlled by MovAlyzeR software, on a laptop computer. Recording handwriting movements on a graphics tablet with non-inking stylus allows for a reliable and sensitive quantitive measure of handwriting metrics and dynamics. The modified task required participants to write the phrase cat and dog with their dominant hand (defined as the hand preferred for writing) in their preferred handwriting style, five times per condition. There were two conditions (1: non-speeded and 2: speeded). The non-speeded condition was considered to be the simplest task (i.e., a measure of baseline ability).	Blocked (5 trials per condition)	Total number of pen lifts	Average spacing inter-word (Metrics) Writing speed		NR	Nonsig	N	0.73 (Good)

Grace et al (2018)	Handwriting task Handwriting movements were recorded using a back-lit, touch-screen, WACOM graphics tablet with non-inking stylus, controlled by MovAlyzeR software. The handwriting experiment included five cursive letter sequencing conditions (1. eeee, 2. eeel, 3. eeem, 4. elel, 5. emem). The 'eeee' condition was considered the simplest task and therefore was used as our baseline measure. Sequences were brief to minimize the potential for muscular and psychological fatigue.	Blocked (8 trials per condition)	average number of total pen lifts	average reaction time; average planning time between same letter transition	NR	ASD vs TD: less average number of pen lifts and planning time between same letter transition	N	0.77 (Good)
Fleury et al (2013)	Drawing task Six different circle drawing conditions were tested in a randomized order. Each condition was explained and demonstrated before the protocol began. For the continuous task, children were instructed to keep drawing circles without stopping and without lifting their pens from the page. For the discontinuous task, children were instructed to draw one circle, then stop at the top, then draw another circle and stop. They continued independently, pausing at the top of each circle, for one minute. They did not lift the pen during the pause. For the fast condition, children were instructed to draw circles as fast as they could.	Variable (NR)	Mean circle drawing time CoV of circle drawing time		Non sig	ASD vs TD: more CoV of circle drawing time	N	0.85 (Strong)
David et al (2009)	Force production task (grip task) The task was demonstrated using a precision grip (using the thumb and index finger to pick-up the object) followed by standardized oral instructions to "pick up the box, placing your thumb and pointer finger on the red circles, and put it down on the blue square".	Blocked (5 trials per conditions)		grip to load force onset latency grip force at onset of load force the peak grip force time to peak grip force	NR	ASD vs TD: longer grip to load force onset latency and greater grip force at onset of load force	N	0.65 (Good)
David et al (2012)	Force production (precision grip force) Children were seated comfortably at a testing table with back and feet supported in a height adjustable chair. The chair was adjusted so that the height of the table was 3–5′ above the elbow. The experimental apparatus was placed on the testing table in front of the child at her/his midline at a distance equivalent to 60% of the child's arm length. he child placed her/his dominant hand on a "start" position which was marked using red	Variable (5 trials per condition)		grip to load force onset latency grip force at onset of load force peak grip force time to peak grip force	NR	ASD vs TD: longer grip to load force onset latency and slower time to peak grip force	N	0.81 (Strong)

	adhesive tape to ensure procedural fidelity and located 5 cm posterior to the experimental apparatus. Simple directions were given—"Pick up 'name of object' (e.g., car, puppy, and Sponge Bob sticker that was stuck on to the experimental apparatus, etc.) and put on the picture of 'name of same object' that you see on the table." Upon hearing the verbal cue, "Go" the child grasped the apparatus, lifted it off the testing platform, and placed it on the target area (brightly colored square with picture of same object).								
Morimoto et al (2020)	Force production task (finger-tapping) To quantify synchronized finger-tapping movements, a magnetic detection system was used (Shima et al. 2009). This system consists of oscillation and detection coils, a magnetic sensor, and a standard personal computer (PC). The system can measure both temporal processing and finger motion dynamics. Finger movement dynamics (i.e., finger velocity and acceleration) were calculated by a differential filter. Participants sat on a chair. Two coils were attached to the thumb and index finger of each individual's dominant hand (Fig. 1a). Participants were instructed to repeat index–thumb tapping in synchronization with onset times of periodic pulse auditory stimuli as precisely as possible. Instructions were presented verbally and by gestures to the participants. As soon as the auditory stimulus presentation began, the participants started finger tapping in synchronization with onset times of auditory stimuli. Measurements were started after finger-tapping waveforms displayed on the PC monitor became stable.	Blocked (30 trials)			aoMax* aoMin* acMax* acMin* SD of aoMax, aoMin, acMax and acMin	NR	ASD vs TD: higher acMax and acMin; higher SD of acceleration parameters .	N	0.81 (Strong)
Mosconi et al (2015)	Force production (precision grip force) Before testing, each participant's maximum voluntary contraction (MVC) was calculated separately for each hand using the average of the maximum force output during three trials in which participants pressed as hard as they could on a dynamometer (Sammons Preston Rolyan). During precision grip force testing, participants viewed a horizontal white force bar that moved upward with increased force and downward with decreased force and a static target bar that was red during	Blocked (3 trials per condition)	Total error	Reaction time Peak rate for force increase Peak rate of force duration Mean sustained	ASD show significantly increased SD of the force variability. Others NR.	ASD vs TD: more total error; greater peak rate for force increase; higher mean sustained force variability	N	0.77 (Good)

	rest and turned green to cue the participant to begin pressing at the beginning of each trial. Participants received two instructions: (1) press the load cells as quickly as possible when the red target bar turns green; and (2) keep pressing so that the force bar stays as steady as possible at the level of the green target bar.			force variability SD of the force variability				
Wang et al (2015)	Force production (precision grip force) During the precision grip test, participants viewed two horizontal bars: a red/green target bar and a white force bar. The white force bar moved upward with increased force, and participants were instructed to press on the load cells as quickly as possible when the target bar turned green so that the force bar reached the height of the target bar. They also were instructed to keep the force bar as close to the target bar as possible until it turned red again, and then to release the load cells as fast as possible.	Blocked (8 trials per condition)		Peak rate for force increase Peak rate of force duration Peak rate of accuracy maximum voluntary contraction	NR	ASD vs TD: lower maximum voluntary contraction	N	0.77 (Good)
Morimoto et al (2018)	Force production (finger tapping task) To quantify synchronized finger-tapping movements, a magnetic detection system was used (Shima et al. 2009). Participants sat on a chair. Two coils were attached to the thumb and index finger of each individual's dominant hand (Fig. 1a). Participants were instructed to repeat index–thumb tapping in synchronization with onset times of periodic pulse auditory stimuli as precisely as possible. Instructions were presented verbally and by gestures to the participants. As soon as the auditory stimulus presentation began, the participants started finger tapping in synchronization with onset times of auditory stimuli.	Blocked (30 trials)		aoMax* aoMin* acMax* acMin* SD of aoMax, aoMin, acMax and acMin	NR	ASD vs TD: higher acMax and acMin; higher SD of acceleration parameters	N	0.81 (Strong)
Stoit et al (2011)	Force production (Grip task) Participants were seated behind a table facing a 17 inch LCD monitor (75 Hz; 1,024 by 768 pixels) at a distance of approximately 80 cm. Immediately in front of and aligned to the midline of the participant a response box was positioned that served as a starting position for the subject's hand in each trial. Both manipulanda had the same shape, but their vertical orientation was reversed. One manipulandum was presented with a small cylinder on top (r = 0.80 cm, height = 1.80 cm) affording a	Variable (12 trials per condition)	Total movement time Total error	Reaction time	NR	ASD vs TD: slower total movement time Non sig for others	Y NR	0.77 (Good)

	precision grip and requiring an approach trajectory from above.							
Togo et al (2019)	Force production (finger-tapping with weight on middle finger) The main task of the current study was a multi-digit force-sharing task, in which participants placed each of the four fingers (from the second to the fifth digit of the right hand) on a force sensor and exerted isometric force on sensors to control a cursor on a computer screen. Participants were asked to trace a 'step function-like' target path with the cursor. A trial consisted of a visual feedback-control and a feedforward-control phase (right half) as described below. In the feedback-control phase of each trial, participants were asked to move the cursor along the target path while minimizing the distance between the cursor and the path.	Variable (50 trials per condition)	Total error	Force ratio	NR	ASD vs TD: more total error; higher force ratio on the 4th finger	N	0.73 (Good)
Salowitz (2015)	Combine tasks (reaching and shape tracing task) Reaching: We designed two experiments that sought to quantify the ability of TD children and children with ASD to invoke strategic compensatory strategies and sensorimotor adaptive compensations during a reaching task that required visuo-proprioceptive reference frame recalibration. "Out-and-back" reaching movements began and ended within a central home target (0.5 cm diameter green circle) that was visible during the entire experiment and was centred along the participant's midline. Tracing: This experiment therefore sought to challenge the ability of TD children and children with ASD to integrate visual information of upcoming target motions into the ongoing sensorimotor control of a tracking task that required strategic compensation for a sudden reflection of the visuo-proprioceptive reference frame. We recorded hand paths while participants used a cursor to track a moving target, which followed an unpredictable and unseen path. Participants were encouraged to rest after each block. To encourage voluntary strategic compensation, participants were told "the cursor will move to the left when you move your hand to the right and vice versa prior to trials in which the reflection was applied.	Variable (shape tracing: NR; reaching: 432 trials- 3 conditions)	Path error and movement time for shape tracing Initial direction error for reaching task		NR	ASD VS TD: more error more initial direction error	Y ASD vs TD: more initial direction error. Others NR	0.89 (Strong)

Mostofsky et al (2000)	Serial Response Time Task Participants were seated in front of a computer screen with four open circles arranged horizontally; the preferred hand responded using four buttons laid out in horizontal fashion, aligned with the circles on the computer screen. Each time a circle illuminated (was filled in) the participant had to press the corresponding button. The circle remained filled in until a button was pushed, upon which the next stimulus would appear after a 1500-ms delay. e. Acquisition of procedural knowledge was measured by the shortening of response time over Blocks 1 through 4 and a rebound in response time from Block 4 to Block 5.	Variable (16 trials- per condition)		Mean reaction time Rebound in response time in the learning phase	NR	ASD vs TD: longer reaction time than TD	Y TD has significantly greater Rebound in response time in the learning phase than ASD.	0.73 (Good)
Wedyan et al (2019)	Machine learning task The mission is embodied in setting the children on modifiable height chair that was adjusted according to the sharers body before desk while the supervisor sat on the fronting side of the desk. Moreover, both parents were existed. The assessment initiates when the sharers' hands, placing at a determined site, stay away from the ball around twenty centimetres. The study mission is consisted of picking the tiny rubber ball that was placed for helping them; the children noticed movement before children fallen it in an open box. The open box was inserted in a clear square box and was sufficiently huge without the need of soft movements. Little passive markers were located on both ulnar and radial parts of the children's wrists, the back of their hand, and on the fourth and fifth hand's bones. Also, four markers were inserted on the box's limits beneath the purposed area while two of them inserted on the ball.	Blocked (10 trials)	Total error	Specificity Sensitivity	NR	NR	N	0.58 (Adequate)

Note: ASD: autistic individiauls; TD : nonautistic individuals; a. practice structure: blocked/random/variable/serial; *DK: don't know PA: peak acceleration; TPA: time to peak acceleration; PD: peak deceleration; TPD: time to peak deceleration PV: peak velocity; TPV: time to peak velocity; NR: not reported; Nonsig: not significant; sdPA: standard deviation of peak acceleration; sdPV: standard deviation of peak velocity; sdPD: standard deviation of peak deceleration; tPHV: percentage time to hand velocity; %TPV: percentage time to peak velocity; AE: absolute error; RP: relative phase, the difference between their respective phases, giving 0° for in-phase and 180° for anti-phase; Apen: approximate entropy; Cross corr*: cross correlation; NJS: normalized jerk score; MGA: maximal grip aperture; NMGA: normalized maximal grip aperture; PTMGA: percent of time to maximal grip aperture; GRF: Ground reaction forces; COP-AP: centre of pressure anteroposterior direction ;COP-ML: centre of pressure mediolateral direction; MI: mutual information; APA: anticipatory postural adjustments; CoV: coefficient of variation (i.e., a quantitative measure of increased variability and irregularity in gait); IC: initial contact; ROM: range of motion; Fin & Fout: grip force inside/outside path; CVin & CVout: grip force variation inside/outside path; aoMax: maximum opening acceleration; aoMin: minimum opening acceleration; acMax: maximum closing acceleration; acMin: minimum closing acceleration

Review Question 1: Do sensorimotor control processes distinguish autistic individuals from non-autistic individuals?

From the 97 included studies, 58% (*n* = 56) of the studies quantified sensorimotor control processes using typical motor control (70%) measurements such as reaction time; force production and movement production measures (e.g., kinematic analysis: peak acceleration; peak velocity). 39 of the 56 studies (70%) used motor control measurement and 33 of the 56 studies (59%) used kinematic analysis. In addition, 16 of the 56 studies (29%) included both motor control and kinematics outcomes (e.g., Foster et al., 2020a; Glazebrook et al., 2006; Gowen et al., 2020).

Motor Planning

Motor planning was a sensorimotor control process related to the computational process of selecting a single solution at all levels within the motor hierarchy to prepare appropriate responses to various environmental events from a period of time that may be consistent with the goal of the task (e.g., reaching towards a cup) (Wolpert, 1997) and was typically quantified using reaction time and peak acceleration (Elliott et al., 2010).

Reaction Time

From all the included studies, 18% (*n* = 17) of the studies reported reaction time in motor planning processes in autistic compared to non-autistic individuals (e.g., Crippa et al., 2013; Glazebrook et al., 2008; Nazarali et al., 2009). Among these studies, over 50% (*n* = 9) showed that autistic participants showed significantly longer reaction times (around 100ms) compared non-autistic individuals (e.g., Glazebrook et al., 2008). Of the 9 studies, there were 3 task types: upper limb movement task (*n* = 5), hand-eye

coordination task (*n* = 3) and handwriting task (*n* = 1). Two studies were also reported the variability of reaction time and found that autistic individuals had more variability in reaction time than non-autistic individuals (Fulceri et al., 2018; Glazebrook et al., 2009). It demonstrated that most of the tasks showed autistic and non-autistic individuals' differences were using upper limb (e.g., arm and hand) and typically autistic individuals was slower in motor planning process than non-autistic individuals. Eight studies were found no significant differences on reaction time in autistic individuals compared to non-autistic individuals.

Peak Acceleration

From all the included studies, 8% (*n* = 8) of the studies reported peak acceleration and time to peak acceleration in autistic individuals compared to nonautistic individuals (e.g., Crippa et al., 2021; Foster et al., 2020a; Glazebrook et al., 2006). Among these studies, 50% (*n* = 4) showed that autistic individuals showed significantly more variability to peak acceleration (1.49 ± 2.38 mm) than non-autistic individuals (e.g., Foster et al., 2020a). Autistic individuals showed significantly lower peak acceleration (669 mm/s2) (Glazebrook et al., 2006), longer time to peak acceleration (44ms) (Glazebrook et al., 2009), and reached earlier peak acceleration (not specify) (Vabalas et al., 2020) than non-autistic individuals. Of all these studies showing significant between group differences, there were 2 task types: upper limb movement task (*n* = 4) and hand-eye coordination task (*n* = 1). Most of the included studies were published from 2016 till 2021, suggesting that kinematics analysis was new to analyse motor planning, comparing to other outcome measures. The studies showed heterogeneity (e.g., different task type, different trials, different measurements) and more studies should be analysed motor planning using kinematic analysis.

Motor Execution

Motor execution was a sensorimotor control process related to execute the motor commands that were required to achieve the goal (e.g., putting a pen in pencil case) once the motor plan had been formed (Gowen & Hamiliton, 2006; Wolpert, 1997), and was typically quantified using force production, peak velocity and peak deceleration (Elliott et al., 2010).

Force Production

From all the included studies, 8% (*n* = 8) of the studies reported force production measures (e.g., grip force, variability of grip force) in autistic individuals compared to non-autistic individuals (e.g., Chen et al., 2016; Van Swieten et al., 2010; Wang et al., 2015). Among these studies, more than 50% (*n* = 5) showed that autistic individuals showed significantly greater grip force (0.12N) (e.g., David et al., 2009), more variability of grip force (not specify) (e.g., Mosconi et al., 2015) and greater grip to load force onset latency (0.26N) (e.g., David et al., 2009). Of these 9 studies, there were 3 task types: precision grip task (*n* = 3), finger tapping task (*n* = 3), and combine tasks on gait and postural control (*n* = 2). Most of these studies used hand, finger, and legs to analyse the force production. All used weight scale or other weighting equipment. It showed that autistic individuals had more variability on both gross (i.e., postural control and gait- balancing skills) and fine motor (i.e., hand grip and finger).

Peak Velocity

From the included studies, 18% (*n* = 17) of the studies were reported peak velocity in autistic individuals compared to non-autistic individuals (e.g., Foster et al., 2020a; Gowen et al., 2020; Hayes et al., 2016). Among these studies, 41% (*n* = 7)

indicated that autistic individuals showed longer time in peak velocity (48ms) and lower peak velocity (303mm/s) (e.g., Glazebrook et al., 2006). Autistic individuals had more percentage time to peak velocity (not specify) and variability than non-autistic autistic individuals, suggesting that peak velocity occurs later in movement in autistic individuals (e.g., Hayes et al., 2016). Of these 7 studies, there were 2 task types: upper limb movement task (*n* = 4) and imitation task (*n* = 3), More than half of the studies were not found any significant differences of peak velocity. The reason could be that the studies showed heterogeneity (e.g., different task type, different trials, different measurements), which they might not be measured on the same level.

Peak Deceleration

From all the included studies, 5% (*n* = 5) of the studies were reported peak deceleration in autistic individuals compared to non-autistic individuals (e.g., Campione et al., 2016; Crippa et al., 2021; Vabalas et al., 2020). Among them, 75% (*n* = 4) showed that autistic individuals showed longer time to peak deceleration (13ms) (Campione et al., 2016) and more variability of peak deceleration (15.1mm) (e.g., Glazebrook et al., 2009). Of these 5 studies, there were 3 task types: upper limb movement task (*n* = 2), reach and grasp task (*n* = 2), and imitation task (*n* = 1) Because of the small number of studies and heterogeneity (e.g., different task type, different trials, different measurements), it showed that kinematic characters were under representatives in literature on sensorimotor control in autism.

Review Question 2: Do sensorimotor learning processes distinguish autistic individuals from non-autistic individuals?

From the 97 included studies, 66% (*n* = 64) of the studies were quantified sensorimotor learning processes using typical movement outcomes such as total movement time; motor control (%) measurements such as reaction time; force production and movement production measures (e.g., kinematic analysis: peak acceleration; peak velocity). 39 of the 64 studies (61%) were used motor control measurement and 24 of the 64 studies (38%) were used kinematic analysis (41%). In addition, 5 of the 64 studies (8%) were included both movement and motor control outcomes (e.g., Gidley Larson et al., 2008; Nazarali et al., 2009); 22 of the 66 studies (33%) were included both movement and kinematics outcomes (e.g., Cook et al., 2013; Vabalas et al., 2020); 10 of the 66 studies (15%) were included all movement outcomes and production measures (e.g., Forti et al., 2011; Glazebrook et al., 2006).

Motor Planning

Motor planning was quantified using reaction time (Elliott et al., 2010). No studies in this systematic review were reported peak acceleration in sensorimotor planning process.

Reaction Time

From all the included studies, 15% (*n* = 15) of the studies reported reaction time in motor planning processes in sensorimotor learning in autistic individuals compared to non-autistic individuals (e.g., Crippa et al., 2013; Glazebrook et al., 2008; Nazarali et al., 2009). Among the studies, 40% (*n* = 6) indicated that autistic individuals showed significantly longer reaction times (around 100ms) compared to non-autistic individuals (e.g., Glazebrook et al., 2008). Of these 6 studies, there were 2 task types: upper limb movement task (*n* = 5) and hand-eye coordination task (*n* = 1).

Motor Execution

Motor execution was typically quantified using total movement time, total error, force production, peak velocity, and peak deceleration (Elliott et al., 2010).

Total Movement Time

From all the included studies, 15% (*n* = 23) of the studies were reported total movement time in motor execution processes in sensorimotor learning in autistic individuals compared to non-autistic individuals (e.g., Fulceri et al., 2018; Stoit et al., 2013). Among the studies, 39% (*n* = 9) showed that autistic individuals had significantly longer movement times compared to non-autistic individuals (e.g., Stoit et al., 2013). Of the 9 studies, there were 2 task types: upper limb movement task (*n* = 7) and force production task (*n* = 2).

Total Error

From all the included studies, 12% (*n* = 12) of the studies were reported total error in motor execution processes in sensorimotor learning in autistic individuals compared to non-autistic individuals (e.g., Foster et al., 2020a). Among these studies, 42% (*n* = 5) showed that autistic individuals made significantly more total error compared to non-autistic individuals (e.g., Foster et al., 2020a). Of these 5 studies, there were 2 task types: upper limb movement task (*n* = 4) and hand-eye coordination task (*n* = 1).

Force Production

From all the included studies, 5% (*n* = 5) of the studies were reported force production in motor execution processes in sensorimotor learning in autistic individuals

compared to non-autistic individuals (e.g., Chen et al., 2016). Among these studies, 40% (*n* = 2) showed that autistic individuals showed significantly longer force onset latency and higher variability compared to non-autistic individuals (e.g., Foster et al., 2020a). Of these 3 studies, there were 2 task types: upper limb movement task (*n* = 2), and an imitation task (*n* = 1).

Peak Velocity

From all the included studies, 5% (*n* = 5) of the studies were reported peak velocity in motor execution processes in sensorimotor learning in autistic individuals compared to non-autistic individuals (e.g., Vabalas et al., 2020). Among the studies, 60% (*n* = 3) indicated that autistic individuals showed significantly lower peak velocity, longer time or more variable to velocity compared to non-autistic individuals (e.g., Dowd et al., 2020; Foster et al., 2020a). Of these 2 studies, there were 2 task types: a combined task with simple movement task and visual distractor task (*n* = 1), and an imitation task (*n* = 1).

Peak Deceleration

From all the included studies, 3% (*n* = 3) of the studies were reported peak deceleration in motor execution processes in sensorimotor learning in autistic individuals compared to non-autistic individuals (Campione et al., 2016; Glazebrook et al., 2009; Zheng, 2015). Among these studies, 67% (*n* = 2) showed that autistic individuals showed more spatial variability in peak deceleration compared to nonautistic individuals (Glazebrook et al., 2009; Zheng, 2015). These studies were both upper limb movement tasks.

Retention

In the context of sensorimotor learning, retention typically referred to the preservation of a specific movement skill or behaviour over a certain period of time. This study included retention phase to examine whether the effect of specific movement skill/behaviours had lasted after a period of time. Motor learning processes in retention was typically quantified using movement outcomes (e.g., total movement time; total error), motor control (e.g., reaction time) and kinematic analysis (e.g., peak acceleration).

From the 97 included studies, 13% (*n* = 13) of the studies were quantified sensorimotor learning processes using typical movement outcomes such as total movement time; motor control (%) measurements such as reaction time; force production and movement production measures (e.g., kinematic analysis: peak acceleration; peak velocity). 9 of the 13 studies (69%) were used movement outcomes as measurement, 7 of the 64 studies (54%) were used motor control measurements and 2 of the 13 studies (15%) were used kinematic analysis. In addition, 7 of the 13 studies (54%) were included both movement and motor control outcomes (e.g., Mosconi et al., 2013; Salowitz, 2015; Stoit et al., 2013); 2 of the 13 studies (15%) were included both movement and kinematics outcomes (e.g., Diaz, 2020; Fukui et al., 2018) and 2 of the 13 studies (15%) were included all movement outcomes and production measures (e.g., Glazebrook et al., 2006; Foster et al., 2020a).

Motor Execution

Motor execution was typically quantified using total movement time, total error, force production, peak velocity and peak deceleration (Elliott et al., 2010).

Total Movement Time

From all the included studies, 4% (*n* = 4) of the studies were reported total movement time in motor execution processes in retention test in autistic individuals compared to non-autistic individuals (Foster et al., 2020a; Hayes et al., 2018; Mosconi et al., 2013; Sparaci et al., 2015). Among these studies, 50% (*n* = 2) showed that autistic individuals needed longer total movement time compared to non-autistic individuals (Foster et al., 2020a; Hayes et al., 2018). Sparaci et al. (2015) found that autistic individuals showed shorter total movement time than non-autistic individuals. These studies were all upper limb movement tasks.

Total Error

From all the included studies, 5% (*n* = 5) of the studies were reported total error in motor execution processes in retention test in autistic individuals compared to nonautistic individuals (e.g., Salowitz, 2015). Among the studies, 60% (*n* = 3) showed that autistic individuals made significantly more total error compared to non-autistic individuals (e.g., Foster et al., 2020a; Hayes et al., 2018). Mostofsky et al. (2000) found that non-autistic individuals had more rebound in response time in the learning phase than autistic individuals. These studies were all upper limb movement tasks.

Peak Velocity

Only one study was reported peak velocity in motor execution processes in retention test in autistic individuals compared to non-autistic individuals. Foster et al. (2020b) found that autistic individuals occurred earlier in the movement for the atypical model than the typical model, whereas non-autistic individuals showed no differences.

Review Question 3: Do autism sensorimotor control and learning processes adapt as a function of practice?

From the 97 included studies, 13% (*n* = 13) of the studies were quantified adaptation of motor control and learning processes across practice using typical movement outcomes, such as total movement time; motor control measurements such as reaction time; force production and movement production measures (e.g., kinematic analysis: peak acceleration; peak velocity). 9 of the 13 studies (69%) were used movement outcome as measures, 7 of the 13 studies (54%) were used motor control measurements and 4 of the 13 studies (31%) were used kinematic analysis (41%). In addition, 3 of the 13 studies (23%) were included both movement and motor control outcomes (e.g., Mosconi et al., 2018; Zhao et al., 2018); 4 of the 13 studies (31%) were included both movement and kinematics outcomes (e.g., Foster et al., 2019; Fukai et al., 2018).

Motor planning

Motor planning was quantified using reaction time (Elliott et al., 2010). No included studies were reported peak acceleration in sensorimotor planning process.

Reaction Time

From all the included studies, 2% (*n* = 2) of the studies were reported reaction time in motor planning processes in adaption of motor control and learning processes across practice in autistic individuals compared to non-autistic individuals (Nazarali et al., 2009; Rinehart et al., 2001). Non-autistic individuals had shorter reaction time from pre-test to post-test, whereas autistic individuals had no differences, using blocked

practice (Rinehart et al., 2001). Nazarali et al. (2009) found no significant differences on reaction time across variable practice in both groups.

Motor Execution

Motor execution was typically quantified using total movement time, total error, force production, peak velocity (Elliott et al., 2010). No other measurements of kinematics analysis (e.g., peak acceleration, time to peak acceleration) were reported the adaption of motor control and learning processes across practice in the included studies.

Total Movement Time

From all the included studies, 6% (*n* = 6) of the studies were reported total movement time in motor execution processes in adaption of motor control and learning processes across practice in autistic individuals compared to non-autistic individuals (e.g., Diaz, 2020; Hayes et al., 2016; Rinehart et al., 2001). Among these studies, 67% (*n* = 4) were reported using blocked practice and were found that both autistic individuals and non-autistic individuals had significantly shorter total movement time from pre-test to post-test (e.g., Rinehart et al., 2001). Autistic individuals had significantly decreased timing variability from pre-test to post-test with block practice (Hayes et al., 2016).

Total Error

From all the included studies, 7% (*n* = 7) of the studies were reported total error in motor execution processes in adaption of motor control and learning processes across practice in autistic individuals compared to non-autistic individuals (e.g., Gidley Larson et al., 2008; Hayes et al., 2016; Taheri-Torbati et al., 2019). Among the studies,

71% studies (*n* = 5) were reported using blocked practice. Both groups had less error in the late phase than early phase of the movement (Gidley Larson et al., 2008; Hayes et al., 2018), and less variability from pre-test to post-test (Taheri-Torbati et al., 2019). Autistic individuals had less error from pre-test to post-test (Hayes et al., 2016). Non-autistic individuals had less error from pre-test to post-test, whereas autistic individuals made no differences (Rinehart et al., 2001).

Force Production

From all the included studies, 2% (*n* = 2) of the studies were reported force production measures (e.g., grip and touch force, COP measures) in adaption of motor control and learning processes across practice in autistic individuals compared to nonautistic individuals (Bojanek et al., 2020; Zhao et al., 2018). Zhao et al. (2018) found that autistic individuals had less variability of speed from pre-test to post-test, whereas non-autistic individuals showed no differences; both groups had increased grip force and decreased in force variation from pre-test to post-test with block practice as a function of practice. Bojanek et al. (2020) found that autistic individuals had increased COP trajectory length and reduced ML sway across stance condition with variable practice.

Peak Velocity

From all the included studies, 3% (*n* = 3) of the studies were reported peak velocity in adaption of motor control and learning processes across practice in autistic individuals compared to non-autistic individuals (Foster, 2019; Diaz, 2020; Hayes et al., 2016). Two studies were reported using blocked practice as a function of adaption. Peak velocity occurred earlier from pre-test to post-test (e.g., Foster, 2019; Hayes et al., 2016). Autistic individuals occurred earlier in the movement for atypical model than

typical model, whereas non-autistic individuals showed no differences between the models (Foster et al., 2020b) using blocked practice.

Discussion

The current systematic review included 97 studies based on three questions on motor control and learning processes in autistic individuals. Of these studies, 91% were found to have ‘strong’ or ‘good’ research strength based on the Kmet et al. (2014) quality assessment process. According to the inclusion criteria, the 97 studies reviewed provided a greater range of sensorimotor tasks, movement outcomes, and kinematic analysis across motor control and learning than the existing meta-analysis (Fournier et al., 2010) that also quantified motor control processes in autism, but principally focused on motor coordination. These results extended the literature by examining the movement outcomes and production measures between autistic and non-autistic individuals to understand of sensorimotor control and learning processes in autism, and how these processes adapted across practice. Review findings could lay the foundation for designing sensorimotor interventions (e.g., the implementation of optimal type of practice for learning in autism) that targeted autism specific differences in motor control and lead to more effective motor learning outcomes for autistic individuals.

Review Question 1: Do sensorimotor control processes distinguish autistic individuals from non-autistic individuals?

To further the understanding of the motor control processes in autism, this systematic review examined motor control outcomes (e.g., reaction time and force

production measures) and kinematic analysis (e.g., peak velocity and time to peak velocity), spanning a broad range of sensorimotor tasks (e.g., upper limb movement tasks, hand-eye coordination, and gait). In 61% (34 from 56) of the included with motor control outcomes, autistic individuals were found to have longer and more variable, reaction times (i.e., a measure of motor planning) when preparing a movement compared to non-autistic individuals (Foster et al., 2020a; Glazebrook et al., 2008; Mari et al., 2003) in various types of sensorimotor tasks (e.g., upper limb movement tasks, gait and postural control) across different age groups, including children, adolescents and adults. Reaction time was a measure of specification of timing of muscular forces during motor planning phase (Elliot et al., 2010). In this phase, the internal representation of expected efference and sensory consequence was formed. The finding of this systematic review suggested that across development, autistic individuals might be slower in the motor planning processes: 1) forming internal representation of expected efference; 2) processing sensory information to form internal representation of the sensory consequence than non-autistic individuals.

Additionally, autistic individuals showed greater spatial variability in key kinematic markers associated with sensorimotor feedforward (i.e., peak acceleration) control than non-autistic individuals. Autism children might have more variability in comparison of expected efference to produced efference and impulse regulation in motor planning process (Elliot et al., 2010) than non-autistic individuals. Therefore, it seemed to be clear that motor planning and feedforward control differences occurring between autistic and non-autistic individuals across different tasks (e.g., upper limb tasks; gait) and measures. The findings relating to more spatial variability and slower

planning in autism, could impact on their acquisition of skills to perform key daily life events (e.g., planning to a cross a road; planning to drink from a cup).

In terms of force production, the findings showed distinctive motor control patterns in autistic individuals when performing precision grip tasks. Generally, force production was more variable in terms of grip to load force, and the timing of grip to load force at movement onset was longer in autism (e.g., David et al., 2009). Force production was suggested to reflect a predictive motor control process where an individual controlled parts of a movement by examining the synchronisation of grip and force load (Gowen & Hamiliton, 2013). Along with reaction time, and spatial variability at peak acceleration, these force findings suggested that autistic individuals demonstrated motor control differences in specifying the accurate force parameters.

Review Question 2: Do sensorimotor learning processes distinguish autistic individuals from non-autistic individuals?

To further the understanding of motor learning processes in autism, the results were based on examining three motor outcomes: movement outcomes (e.g., total error and total movement time), motor control outcomes (e.g., reaction time and force production measures) and kinematic analysis (e.g., peak velocity and time to peak velocity). These outcomes were included from studies across a broad range of sensorimotor tasks (e.g., upper limb movement tasks, hand-eye coordination, and gait), and importantly how learning processes adapted across practice leading to short term (post-test results), and long-term (retention test results), changes in motor learning.

Compared to non-autistic individuals, the data from the narrative synthesis related to motor outcomes revealed 39 studies that were used total movement time (*n* = 23) and total error (*n* = 12) to measure motor learning processes. For total movement time, which was a timing variable that quantifies motor execution (Elliot et al., 2010), autistic individuals generally executed movements that were slower than non-autistic individuals (e.g., Rinehart et al., 2001). For total error, which also calculated movement variability, autistic individuals were generally less accurate and more variable in movement execution than non-autistic individuals (Hayes et al., 2016). Nevertheless, some studies (n = 21) showed no significant differences in movement execution between autism and non-autistic individuals (e.g., Fukui et al., 2013; Johnson et al., 2015). Investigation into these studies showed that most were using different types of tasks (e.g., reach and grasp task, hand-eye coordination, and handwriting tasks) with different measurements, and number of trials (e.g., 15 trials with a hand eye coordination task. e.g., Fukui et al., 2013; 5 trials with a handwriting task. e.g., Johnson et al., 2015). Each study had different number of trials, resulting different practice duration. Also, it suggested that the movement time and total error as movement execution measures shared more general information of the movement. More motor measurements were suggested to investigate the motor learning process in autism.

Compared to non-autistic individuals, the results from the narrative synthesis related to motor control outcomes revealed 24 studies that were used reaction time (*n* = 23) and force production (*n* = 12) to measure motor learning processes. For reaction time, which was a timing variable that inferred cognitive and motor planning processes, autistic individuals generally showed longer reaction time that non-autistic individuals (Glazebrook et al., 2018). For force production, autistic individuals generally had a

longer grip-to-load-force time at movement onset, and with greater variability, than non-autistic individuals (Chen et al., 2016). Investigation into these studies showed that most were different types of tasks (e.g., postural control tasks on a force platform, reach to grasp task, hand-eye coordination task finger-tapping task.) with different measurements and various number of trials, which might affect the motor learning processes.

Compared to non-autistic individuals, the results from the narrative synthesis related to kinematic analysis revealed 26 studies that were used peak acceleration and time to peak acceleration (*n* = 7), peak velocity and time to velocity (*n* = 12), and peak deceleration and time to deceleration to measure motor learning processes. For peak acceleration and time to peak acceleration, which was a kinematic variable that quantified motor planning and feedforward control, autistic individuals generally had lower peak acceleration, and more variability than non-autistic individuals (Dowd et al., 2020; Foster et al., 2020a). For peak velocity and time to peak velocity, which provided an indication of motor planning around feedforward and feedback motor control, autistic individuals generally had lower peak velocity and more variability than nonautistic individuals (Foster et al., 2020a; Vabalas et al., 2020). From the included studies that were used kinematic analysis, 57% were found significant differences between autism and non-autistic individuals. These studies were used upper limb movement tasks with goal-directed movement (Foster et al., 2020b; Glazebrook et al., 2008).

Seven studies that showed no significant differences between autistic and non-autistic individuals (Stoit et al., 2011) investigated motor control during gait (e.g., Nor et al.,

2016; Johnson et al., 2015) across a limited number of 5-10 trials. There was no theoretical reason (Elliott et al., 2010) why different control processes should operate across upper limb and lower limb tasks, so further examination using similar measurements metric would elucidate on this difference.

Although there were some differences in motor control during learning, Gidley Larson et al. (2008) found that after a period of adaption, autistic individuals had significantly improved motor accuracy when performing a goal-directed throwing task. Haswell et al. (2009) also showed that autistic individuals learned to adapt to unexpected forces perturbations during a manual aiming task. Similarly, there was reduction in reaction time in autism after adaption phase and the autistic individuals showed no significant differences with non-autistic individuals (Brown et al., 2010; D'Cruz et al., 2009; Rinehart et al., 2001). Taken together, these findings suggested that autistic individuals successfully modify motor control differences. This indicated that processes related to feedforward and feedback control were operational across practice, and in fact may even more effective (see Practice Type and Adaption section below) in certain types of practice environments.

In terms of the retention test, more than half of the studies suggested that autistic individuals had more difficulties in executing a movement correctly and precisely (e.g., longer movement time and more errors) than non-autistic individuals. Foster et al. (2020a) found that, even though autism exhibited shower movements across acquisition and retention test than non-autistic individuals, both groups showed comparable magnitudes of adaption when imitating atypical and typical biological

motion, specifically when the experimental trials were using block practice as type of practice.

Review Question 3: Do autism sensorimotor control and learning processes adapt as a function of practice?

By reviewing the within-group differences across practice in the studies, autism significantly improved motor performance (e.g., shorter movement time, shorter reaction time and less error when conducting the movement) with blocked practice. Foster et al. (2020) compared blocked practice with random practice as a function of adaption for motor learning in autism using an upper limb movement task. Autistic individuals were significantly more accurate when performing in blocked practice. As mentioned above, reduced variability in peak velocity was found in autism through blocked practice (Wild et al., 2012). In terms of variable practice, autism increased variability in trajectory length and reduced sway across stance condition with variable practice (Bojanek et al., 2020). Nevertheless, only one study was reported the effectiveness of variable practice. More research on the function of practice would be conducted in the future to examine the effective of certain practice.

Study Limitation

Several studies (e.g., Diaz., 2020; Pierno et al., 2008) were found no significant differences in any of the movement outcomes and production measures in between autistic and non-autistic individuals, making it difficult to establish trends (e.g., autistic children had longer reaction time than non-autistic individuals.) in sensorimotor control and learning. This could be also due to small sample sizes, that can lead to lower statistical power in the included studies (e.g., Chen et al., 2016; Lidstone et al., 2020).

Additionally, publication bias could lead to an underrepresentation of non-significant findings, that could affect the robustness of the review findings. The possible explanation for the discrepancies between study results was because of heterogeneity across studies on 1) type of tasks, 2) number of trials, and 3) the quality of study design and analysis methods.

Conclusion

In sum, the review provided evidence that autistic individuals could be distinguished with non-autistic individuals on motor control and learning processes. Blocked practice could be served as a function of adaption of motor learning in autism. The movement outcomes and production measures showed autistic individuals sensorimotor processes operated differently than non-autistic individuals. Further research with larger sample sizes, more consistent task designs, and methodologies such as kinematic analysis were important to be conducted to investigate the underlying motor control processes in autism. These findings could inform the development of more targeted motor interventions in autism.

Chapter 4: Visuomotor Integration and Literacy Skills in Autistic Children aged 7 to 11 years old

Introduction

Previous research indicates that autistic children experience distinct challenges in various aspects of visuomotor integration (VMI), including visuomotor planning (Fabbri-Destro et al., 2009), coordination (Rinehart et al., 2006a), and imitation learning (Izawa et al., 2012; Lidstone & Mostofsky, 2021). The findings of the prior systematic review identified the differences of sensorimotor control and learning among autistic individuals, suggesting that such differences may affect the formation of internal action models (Elliott et al., 2020) and influence how autistic individuals control (Glazebrook et al., 2008) and learn (Foster et al., 2020) visuomotor behaviours. These differences are also observed in VMI, which involves the coordination of visual and motor information (Bullock et al., 1993; Shin et al., 2009).

Although VMI differences in autism affect behaviours such as aiming to targets (i.e., using a door handle), bouncing a ball, and copying a teacher modelling a movement (i.e., holding a pen), it is not clear if VMI differences in autism influence academic attainment as per non-autistic school-aged children (Grissmer et al., 2010; Son & Meisels, 2006). In non-autistic school-aged children, data from Beery motor assessments (Beery VMI, 2010), which quantifies VMI proficiency using visuomotor tracing and copying activities, showed children who were more accurate at tracing and copying symbols were more accurate at literacy skills such as letter-word identification, reading comprehension, handwriting quality and fluency (Cameron et al., 2012; Carlson et al., 2013; Grissmer et al., 2010; Kaiser et al., 2009). In addition to these motor-literacy associations, it has also been shown that children's VMI skills was a predict later literacy development, including letter-word identification, reading comprehension,

sound awareness, handwriting quality and fluency (Cameron et al., 2012; Carlson et al., 2013; Kaiser et al., 2009).

The transfer of VMI (see Schmidt, 1977; 2003; Elliott et al., 2010) processes to literacy-related skills (e.g., word reading, reading comprehension and handwriting) is suggested (Kaiser et al., 2009; Tseng and Murray, 1994; Waterman et al., 2014; Wolf et al., 2009) to be underpinned by domain general sensorimotor processes (e.g., attentional, intentional, and sensorimotor processes) that are recruited to control VMI activities (e.g., copying), in addition to orthographic and memory processes that are engaged during writing (Medwell et al., 2009). For example, during copying, which is a voluntary imitation mechanism, a participant engages attentional, intentional, and sensorimotor processes in order to create a new internal action plan of the observed stimulus (i.e., a symbol; a letter; or a person) (Iacoboni, 2009; Keysers et al., 2018; Schaal et al., 2003). During the process of observing a symbol (e.g., triangle), sensorimotor processes are engaged to represent the visuospatial properties of the symbol within a sensorimotor system linking perception with action (Becchio et al., 2007). These sensorimotor processes are then recruited to control the production of fine motor movements [i.e., precision of small finger movements to utilise a tool (e.g., pen/pencil)], and associated visual feedback processing, when writing the symbol on paper or a tablet. Thus, it is therefore suggested that the development and learning of certain literacy skills is related to a greater VMI proficiency (Cameron et al., 2012; Carlson et al., 2013; Kaiser et al., 2009).

Although there is evidence of the relationship between sensorimotor processes and literacy in non-autistic children (Carlson et al., 2013; Grissmer et al., 2010; Waterman et al., 2014) and those with developmental coordination disorder (De Waal

et al., 2018; Fletcher-Flinn et al., 1997), there has not been an examination of VMI and literacy skills (e.g., word reading, reading comprehension and handwriting) in autistic children aged 7 to 11 years old. The aim of the present research was therefore to extend the examination of VMI and literacy by also examining the predictors of literacy skills in autistic children aged 7 to 11 years old using hierarchical regression. To do this, a standardised assessment (e.g., Beery) of VMI was assessed along with key control variables [e.g., intelligent quotient (IQ), executive function (EF) and autism severity measures]. For literacy, word reading was measured using the British Ability Scales-3 (BAS-3) reading test, reading comprehension was measured using the York Assessment of Reading Comprehension (YARC) reading test, and handwriting quality and fluency was measured using the Detailed Assessment of Speed of Handwriting (DASH) handwriting test.

The research question was: What are the predictors of literacy skills in autistic children aged 7 to 11 years old? It is hypothesised that VMI, IQ and EF were predictors (see Arán Filippetti & Richaud, 2015; Carlson et al., 2013) of literacy skills in autistic children aged 7 to 11 years old.

Methods

Power Analysis / Sample Size

A power analysis using G*Power (Faul et al., 2007) was used to determine a minimum sample size for the study. The goal was to obtain .95 power to detect a large effect size of .80 at the standard .05 alpha error probability. The software G*Power indicated a sample size of 25 was required when conducting multivariate regression analysis. Based on previous studies, this n was also typical when using lab-based tasks

with these groups (Foster et al., 2020a, 2020b; Glazebrook et al., 2009; Hayes et al., 2018).

Participants and Recruitment Process

Sixty-two children (see Table 3) were recruited from 4 autism special schools and 1 mainstream school in London. Chi-square tests were performed to examine difference of categorical data (i.e., gender, whether English as their first language) with verbal and nonverbal participants. Fisher's exact test was applied if the assumptions were violated (i.e., the assumption of chi-square is that no more than 20% of cells have frequencies <5). The children were recruited based on the following inclusion criteria: (1) aged between 7 and 11 years old; (2) have a formal diagnosis of autism spectrum disorder that made using a standardised diagnostic instrument (e.g., ADOS), or using established diagnostic criteria (e.g., DSM or ICD) by a specialist (e.g., a clinical psychologist, paediatrician); (3) children can understand verbal instructions and perform pen/paper/tablet copying and tracing activities (i.e., copying and tracing a straight line using a pen). For the recruitment process and following a period of 6 months familiarisation within schools, I first worked with teaching staff (e.g., head teacher, assistant headteacher, or research lead) to contact parents/caregivers who met the inclusion criteria. Additionally, social media platforms (i.e., X/Twitter; Facebook) were used to recruit participants. Following contact, a participant information sheet and consent form were sent to the parents/caregivers to explain the aims of the study, the activities that their child/children would engage within the study, and information on how and whether to volunteer. Ethics was received and approved by IOE, Faculty of Education and Society, University College London, with data protection No. Z6364106 on 18th February 2023.

Table 3. Demographic Information of Verbal and Nonverbal Participants by Gender, English as First Language and Age (Mean)

Domain	Verbal	Nonverbal	X^2/t	*p*
Participant	N = 51	N = 11		
Gender	M = 41 F = 10	M = 9 F = 2	/	1.00
English as first language	Yes = 36 No = 15	Yes = 8 No = 3	/	1.00
Age	9.99 (1.58)	9.08 (1.83)	t (60) = 1.67	.10

Materials and Measured Variables

Autism Severity 1: Childhood Autism Rating Scale (CARS)

The Childhood Autism Rating Scale (CARS; Schopler et al., 1986), was completed by parents/caregivers to assess the presence and severity of symptoms of autism spectrum disorder. The CARS questionnaire consists of 15 question items corresponding to autism symptoms, including social, emotional, adaptive, cognitive and communicative functions. It is a 4-point rating scale, ranging from 1 to 4, where 1 indicates “no evidence of difficulty or abnormality/ age-appropriate behaviours”, and 4 indicates “several abnormality/inappropriate behaviours”. Raters can select midpoints scores (1.5, 2.5 and 3.5) when the child’s behaviour appears to fall between two rating categories. CARS provided a ‘total’ score (range: minimum of 15 to a maximum of 60), which indicated autism severity. Scores below 30 indicated non-autism, scores between 30 and 36.5 indicated mild to moderate autism, and scores from 37 to 60 indicated severe autism.

Autism Severity 2: Social Responsiveness Scale, Second Edition (SRS-2)

The Social Responsiveness Scale, Second Edition (SRS-2; Constantino & Gruber, 2012), was completed by parents/caregivers to identify social impairment associated with autism spectrum disorder and to quantify severity. The SRS-2 questionnaire consists of 65 items, ordinally scaled (1 = “not true” to 4 = “almost always true”) corresponding to the severity of autism traits. SRS-2 provided raw scores in 7 domains (e.g., awareness, cognition, and motivation), which are then converted into T-scores (range: minimum of 32 to a maximum of 114) that indicated autism severity. T-scores less than or equal to 59 indicated non-autism, T-scores between 60 and 65 indicated mild autism, T-scores between 66 to 75 indicated moderate autism, and T-scores greater than or equal to 76 indicated severe autism.

Intelligence Quotient: Wechsler Abbreviated Scale of Intelligence (WASI)

The Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) was used to assess and measure intelligence quotient (IQ). Four subtests were assessed: (1) vocabulary (42 – item with 4 images and 37 words); (2) block design (13 – item); (3) similarities (26 – item with 4 images and 22 verbal item); and (4) matrix reasoning (35 – item). WASI provided a full-scale intelligence quotient (FSIQ) score, along with verbal (including vocabulary and similarities subtests, VIQ) and performance (including block design and matrix reasoning subtests, PIQ) scores. T-scores are then calculated for each of the four subtests, with a mean of 50 and a standard deviation of 10. The FSIQ provided an overall estimate of general intellectual ability, with a mean of 100 and a standard deviation of 15. Based on the FSIQ scores, performance is described as: “Superior” (scoring 130 and beyond); “Very High” (scoring 120 and 129);

“Bright Normal” (scoring 110 and 119); “Average” (scoring 90 and 109); “Low Average” (scoring 80 and 89) and “Borderline Mental Functioning” (scoring 70 and 79).

Executive Function (EF): Behaviour Rating Inventory of Executive Function – Second Edition (BRIEF-2)

Autistic individuals were found to have difficulty in several executive components, including planning, shifting and inhibition (Kenworthy et al., 2008), that were also essential to visuomotor goal-directed behaviours. Executive function impacted on motor control and learning (Gonzalez et al., 2021), as well as on cognitive skills and daily function, which further influence academic performance and social outcomes (Best, 2010). In this study, executive function was measured to investigate its effect on literacy skills in relation to visuomotor integration skills. This examined both the individual and combined effects of executive function and visuomotor integration on literacy skills. Working memory is a crucial component of executive function and is strongly associated with communication, learning, and visuomotor integration skills (Alloway, 2007). Lê et al (2021) showed that fine motor skills influence literacy through working memory and handwriting, mediating both low-level (reading, spelling) and high-level (reading comprehension, written production) literacy processes. Thus, working memory score, alongside executive function total score, were examined in the following analysis.

The Behaviour Rating Inventory of Executive Function – Second Edition (BRIEF-2; Gioia et al., 2015) was completed by parents to assess and measure executive function. The BRIEF-2 (ages 5 to 18 years) is a questionnaire consisting of 86 items that measured 8 aspects of executive function skills: inhibit, shift, emotional

control, initiate, working memory, plan/organise, monitor and organisation of materials. Item level scores are rated on a 3-point Likert scale: 1) Never; 2) Sometimes; 3) Often. The BRIEF-2 scores for each scale were converted to T scores. Based on the T scores, EF is described as: higher than 70 (clinically elevated), 65 – 69 (potentially clinically elevated), 60 – 64 (mildly elevated) and less than 60 (normal range).

VMI Performance: The Beery-Buktenica Developmental Test of Visual-Motor Integration – Sixth Edition (Beery VMI)

The Beery-Buktenica Developmental Test of Visual-Motor Integration Sixth Edition (Beery VMI; Beery et al., 2010) was used to assess the extent to which individuals can integrate visual and motor abilities. The tool was chosen as it is applicable to children, adolescents, adults, and seniors, aged 2–100 years. The Beery VMI test consisted of 30 geometric designs of increasing complexity that participants were asked to copy. It was administered to individuals and took approximately about 1015 minutes to complete. One additional standardised test, the Beery VMI Motor Coordination Test (Beery VMC), was also used as it facilitates the comparison of an individual's separate motor performance skills. In this test, participants were asked to trace geometric shapes (same used in the Beery VMI) with a dashed outline using a pencil without an eraser and it took approximately 5 – 10 minutes to complete. In terms of scoring, one point is calculated for each correctly copied and traced item. Scoring is stopped when a child performed 3 consecutive failures. A "total" raw score was first calculated for copying and tracing task, followed by a conversion to a standard score. Based on the standard score, performance is described as: "Very High" (scoring 130 and beyond); "High" (scoring 120 and 129); "Above Average" (scoring 110 and 119);

“Average” (scoring 90 and 109); “Below Average” (scoring 80 and 89); “Low” (scoring 70 and 79); “Very Low” (scoring 69 and below).

Literacy Skills Assessments/Outcome Measures (Dependent Variables)

Word Reading: British Ability Scale - Third Version (BAS-3) Word Reading Subtest: British Ability Scale - Third Version (BAS-3; Elliot & Smith, 2011) word reading subtest was used to assess and measure the word reading. BAS-3 consists of standardised cognitive tasks including measures of single-word reading, spelling and number skills. The word reading subtest of BAS-3 (ages 5 to 18) requires the child to read aloud a series of words presented on a card. The child must correctly pronounce the words with emphasis only on the correct syllable or syllables. Each correct response was recorded as 1 point and 0 point otherwise. Total number of words read correctly form the raw scores. Raw scores were then converted to the standard score, representing the word reading score.

Reading Comprehension: York Assessment of Reading for Comprehension (YARC) Passage Reading Test: York Assessment of Reading for Comprehension (YARC; Snowling et al., 2012) passage reading test was used to assess and measure the reading comprehension. YARC passage reading test (ages 5 to 11) is a reading assessment on word recognition (single word reading test), reading fluency and reading comprehension in children. Children first read a series of words and the total number of correctly pronounced words are calculated, which determine the passage difficulty. Then they read two passages and answer a series open-ended comprehension question. The total number of correctly answered comprehension

questions are calculated, which form the raw score. Raw scores were then be converted to the standard score, representing the reading comprehension score.

Handwriting Speed: Detailed Assessment of Speed of Handwriting (DASH)

Alphabet Writing Test: Detailed Assessment of Speed of Handwriting (DASH; Barnett et al., 2007) alphabet writing test was used to assess, and measure handwriting speed. DASH alphabet writing task (ages 9 to 17) was administered to measure writing speed. Children are asked to write the lower-case alphabet in the correct order from memory as many times as possible in 1 minute. A total number of correctly sequenced letter is recorded, representing the handwriting fluency and quality score. In the current study, as there were autistic children young than age 9, DASH raw scores were used for further analysis.

Procedure

All children who volunteered for the study performed the activities within their own school. I first received permission from the school headteachers to pilot-test the measurement activities with several children to refine the process. On each testing day, I first spent time (~30 mins) in a class to familiarise herself with the teaching staff and children. She then worked with the teaching staff to ask each child whether and when they would like to take part in the study. After agreeing to take part in the study, each child individually moved to a small room located within the classroom where the measurement activity was set-up on a small table next to a chair. Each child was invited to sit at the table and then received task instructions from I on how to perform each specific measurement. The child was asked to confirm they understood the instructions, and if needed, they were provided with additional prompts to clarify the process. Based

on pilot testing, each measurement was performed separately and only one measurement activity was located at the table to promote attention on task. The 5 activities (Beery VMI; BAS-3; YARC; DASH; WASI) were performed in a randomised order and I followed the specified instructions from each standardised manual. On average, the total time to complete the 5 tasks was 2 hours per child and these tasks were performed on separate days at each school. The tasks were: 1) copying and tracing activities based on **Beery VMI** (e.g., copying and tracing a line using a pen/pencil); 2) word reading activities based on **BAS-3** (e.g., read a list of words out loud); 3) reading comprehension activities based on **YARC** (i.e., read two passages and answer 8 questions for each passage); 4) handwriting activities based on **DASH** (i.e., write lower-case alphabet letters in the order from a to z in one minute); 5) IQ-related activities based on **WASI** (e.g., read a word out loud and explain the meaning of this word). As stated, the parents/caregivers completed the questionnaires of CARS, SRS-2, and BRIEF and returned the forms to the classroom teacher.

Data Analysis

To answer the research question, bivariate correlations and hierarchical multiple regression analyses were conducted to 1) assess the strength and direction of relationships between individual pairs of variables; 2) examine whether variables were associated with dependent variables, and 3) the degree to which variables accounted for the variance in autistic children's literacy skills.

Bivariate Correlations

Prior to hierarchical multiple regression analyses, bivariate correlations of demographic, cognitive, VMI, and literacy-related dependent variables (i.e., word

reading; reading comprehension; handwriting fluency) were conducted to assess the strength and direction of relationships between individual pairs of variables (Bewick et al., 2003; Shmueli, 2010). This initial correlation analysis aimed to identify potential associations among the variables and provide insights into the nature of their interdependencies, laying the groundwork for the subsequent hierarchical multiple regression analysis.

Hierarchical Multiple Regression

Hierarchical multiple regression analyses were used to examine whether variables [e.g., demographic information (gender, age, ethnicity, first language), IQ, EF, Beery VMI] predicted autistic children's literacy skills (i.e., word reading, reading comprehension and handwriting) and the degree to which the variables accounted for the variance in autistic children's literacy skills.

Results

A minority of the recruited children were nonverbal and as such were not able to take part in the formal examination of word reading, reading comprehension and verbal IQ. Thus, an examination (see Dockrell et al., 2014) of the verbal and nonverbal children are presented first to establish any measurement differences.

Analysis of Verbal and Nonverbal Children

Table 4 presents the mean and standard deviation (SD) data and the significant differences for motor, literacy (handwriting fluency), autism severity, IQ (performance IQ) and executive function measures for verbal and nonverbal participants. As indicated,

the verbal participants had significantly higher scores on motor measures (i.e., VMI & VMC), handwriting fluency, performance IQ, working memory, and GEC (global executive composite; an overarching summary score that includes all the BRIEF executive function components) than nonverbal participants. There were no other significant differences between these groups. Moreover, as there are 1) unequal number between verbal (*n* = 51) and nonverbal (*n* = 11) participants, and 2) the focus of the current study investigated the contribution of motor skills contribution on three literacy skills (i.e., word reading, reading comprehension, and handwriting) in autistic children at Key Stage 2, further analyses are reported for verbal participants.

Table 4. Mean Differences of Motor, Literacy, Autism Severity, IQ, and Executive Function Measures between Verbal and Nonverbal Participants

Domain	**Measure**	**Verbal**	**Nonverbal**	***t***	***p***
Motor Measures	VMI	74.20 (18.72)	50.18 (8.72)	t (60) = 6.47	<.001
	VMC	55.67 (12.18)	45.18 (.60)	t (60) = 6.12	<.001
Literacy Measure	Handwriting fluency	18.73 (13.48)	1.70 (2.16)	t (59) = 8.48	<.001
	Reading Comprehension	80.14 (9.36)	/	/	/
	Word Reading	76.35 (10.66)	/	/	/
Autism Severity	SRS	69.80 (11.84)	75.30 (9.62)	t (58) = -1.38	.17

	CARS	42.88 (10.24)	48.22 (9.28)	t (49) = -1.54	.15
IQ Measures	Performance	84.00 (17.81)	69.90 (11.16)	t (57) = 3.24	.04
	Verbal	77.02 (16.15)	/	/	/
Executive Function Measures	Working Memory	60.38 (10.45)	68.09 (9.98)	t (59) = -2.30	.04
	GEC	62.94 (11.85)	70.09 (11.36)	t (59) = -1.83	.07

Analysis of Verbal Children

Handling Missing Data

Missingness analyses were used with the verbal participants (*n* = 51). Other than YARC-reading comprehension measure (missing on 13.7%), and CARS autism severity measure (missing on 17.6%), the missing data for other variables were less than 5%, which is inconsequential to the overall results (Tabachnick & Fidell, 2013). YARC showed that it had significant relationships with handwriting fluency, working memory and executive function. CARS had no significant relationships with other variables. Both missing data of reading comprehension and CARS showed no association considering gender and whether first language is English. Additionally,

Little's MCAR was performed and indicated that missing data was random ($\chi 2$ (71) = 71.33, p = .45). A multiple imputation (MI) mechanism was used for data that were missing completely at random or missing at random. Also, MI accommodated auxiliary variables (i.e. variables not containing missing data) in the imputation model to account for any patterns or relationships between these variables and the missingness of the data (Huges et al., 2019). The data set after MI were used for further analysis.

Age

Exploration of the age of participants indicated variation in the number of participants from age categories (e.g., 7 - 8, n = 5; 10 -11, n = 13; 11 +, n = 15) and as such may influence the outcome of the overall regression analyses. Based on the previous literature, participants were separated into two age groups: (1) less than and equal to 9 (<= 9 yrs, n = 24); (2) more than and equal to 10 (>=10 yrs, n = 27). In this case, both age groups had similar numbers of participants and thus were added to the following analyses. The age variable was treated as a categorical variable using the 'dummy variable' function in SPSS, called age category variable, with participants less than and equal to 9 (<=9 yrs) coded as "0", and participants more than and equal to 10 (>=10 yrs) coded as "1". Dummy variables are used to replace the encoded categorical variables to some numeric values (generally represented by 0 and 1), so that the encoded categorical values do not influence the impact on prediction.

Composite Scores

Composite scores were computed for some measures as they had similar underlying common constructs (e.g., VMI and VMC) based on theoretical understanding and the outcome (see below) of bivariate correlation analysis (Raykov

et al., 2016). Z-scores were then used to convert the data into the same units for all included measurements (Andrade, 2021). A new composite score (by adding z-score of each measure) was used in the regression analysis. Given the significant high value correlations between 1) word reading and reading comprehension (r = .74); 2) VMI and VMC (r = .54); 3) SRS and CARS (r = .86), composite scores were computed to represent 'reading', 'motor', and 'autism severity' domains.

Bivariate Correlations

The two dependent variables for literacy are *reading* and *handwriting fluency*. Prior to hierarchical multiple regression analyses, bivariate correlations between independent variables, including demographic, cognitive, VMI variables (e.g., age category, FSIQ and VMI composite scores) and dependent variables, including *reading* composite score (i.e., word reading and reading comprehension) and *handwriting fluency* was conducted to assess the strength and direction of relationships between individual pairs of variables. The correlation analyses were performed to identify potential associations among the variables and to provide insights into the nature of their interdependencies, which is used to inform the rationale for the subsequent hierarchical multiple regression analysis (see Richardson et al., 2015). Predictors for the regression analysis were selected based on the theoretical rationale and significant correlations.

As illustrated in Table 5, the predicting variables that were significantly correlated with the dependent variables (i.e., reading and writing) formed the basis of the regression model. In terms of *reading*, the correlated and predicting variables for regression analysis were age category (r = -.28), autism severity (r = -.33), GEC (r =

-.41), FSIQ (*r* = .76), VMI (*r* = .53) and *handwriting fluency* (*r* = .44). In terms of *handwriting fluency*, the correlated and predicting variables for regression analysis were autism severity (*r* = -.39), GEC (*r* = -.34), FSIQ (*r* = .38), VMI (*r* = .50) and *reading* (*r* = .44).

Table 5. Bivariate Correlations for Demographic, Cognitive, VMI, Reading and Handwriting Fluency.

	1	2	3	4	5	6	7	8	9
1.Reading	--								
2.Gender	-.01	--							
3.Age_Cat	-.28*	-.23	--						
4.English as first language	.03	.22	.18	--					
5.Autism Severity	-.33*	.01	-.18	.09	--				
6.GEC	-.41**	.08	-.19	-.01	.75**	--			
7.FSIQ	.76**	-.12	-.20	-.05	-.42**	-.46**	--		
8.VMI	.53**	.02	.06	.05	-.30*	-.38**	.64**	--	
9.Handwriting fluency	.44**	-.22	.25	.09	-.39*	-.34*	.38**	.50**	--

*p < .05; **p < .01; Reading: reading composite score of YARC reading comprehension and BAS word reading reflecting reading proficiency; Gender: Participant's gender; Age_Cat: Age Category, coded as 0 = younger group, 1 for older group; English as First Language: whether participant speaks English as their first language (1 = Yes, 2 = No); Autism Severity: composite score of SRS and CARS measuring the severity of autism symptoms; GEC (Global Executive Composite): A measure from the Behaviour Rating Inventory of Executive Function (BRIEF) that assesses executive functioning abilities; FSIQ (Full-Scale IQ): A composite verbal and performance IQ score from WASI cognitive testing; VMI (Visual-Motor Integration): A measure of the integration of visual and motor skills using Beery VMI; Handwriting Fluency: the number of accurate lower-case in sequence alphabet letters from DASH alphabet task.

Handwriting Fluency and Age Category as an Interaction Term

For *handwriting fluency*, and because the DASH standardised measure is only age normed to children aged between 9 -16 years old, raw scores were used in the analysis because there were 16 children younger than 9 years. Therefore, to ensure that age was accounted for in the DASH analysis as per all other standardised measures, an interaction term was applied to the regression model. Thus, a new variable was computed to represent the interactive effect of age and the variable for *handwriting fluency*. As the age-category variable represented age, the main effect of age-category, *handwriting fluency*, and the interaction term (i.e., age category * handwriting fluency) were used in the regression analysis for *reading*. In terms of *handwriting fluency*, age-category was entered into the regression model as it is the only variable that does not account for age.

Data Screening for Hierarchical Regression

To run the analyses, the raw data were first screened to establish if the assumptions of hierarchical regression were violated. The following tests did not reveal any violations: 1) independence of residuals (Durbin–Watson statistic of 1.59), 2) multivariate outliers/influential data points and 3) normality of residuals. The examination of multicollinearity indicated that FSIQ was significantly correlated with verbal IQ (r = .87) and performance IQ (r = .85), and working memory was significantly (r = .75) correlated with GEC (i.e., executive function total score). Therefore, FSIQ and executive function total scores were included in the regression model.

Hierarchical Multiple Regression

Hierarchical regression was conducted to explore predictors (e.g., age category, FSIQ and VMI) of *reading* and *handwriting fluency* (dependent variables DVs) of autistic children aged 7 to 11 years old. Various IVs (i.e., demographic information, autism severity, IQ, executive function, VMI, literacy-related variables) were added in different model orders to examine which IV accounted for the greatest variance for a DV.

In terms of a statistical approach, there are many reported methods for investigating the order in which to add the variables into the nested regression model (Achen, 1982; Grömping, 2015; Miller, 1984). For example, Achen (1982) suggested that the 'level of importance' (the level of the influence of variables on DVs) and 'dispersion importance' (judge the predictors based on standardised coefficient) are key considerations, along with the model order being based on the nature of the research questions (see Holgersson et al., 2015). Taken together, different model orders were examined using hierarchical regression based on our submodels (i.e., IQ, EF, VMI, and literacy-related variables) were tested in 24 different permutations: (1) GEC-FSIQ-VMI-literacy; (2) GEC-FSIQ-literacy-VMI; (3) GEC-VMI-FSIQ-literacy; (4) GEC-VMI-literacy-FSIQ; (5) GEC-literacy-FSIQ-VMI; (6) GEC-literacy-VMI-FSIQ; (7) FSIQ-GEC-VMI-literacy; (8) FSIQ-GEC-VMI-literacy; (9) FSIQ-VMI-GEC-literacy; (10) FSIQ-VMI-literacy-GEC; (11) FSIQ-literacy-GEC-VMI; (12) FSIQ-literacy-VMI-GEC; (13) VMI-FSIQ-GEC-literacy; (14) VMI-FSIQ-literacy-GEC; (15) VMI-GEC-FSIQ-literacy; (16) VMI-GEC-literacy-FSIQ; (17) VMI-literacy-GEC-FSIQ; (18) VMI-literacy-FSIQ-GEC; (19) literacy-FSIQ-GEC-VMI; (20) literacy-FSIQ-VMI-GEC; (21) literacy-

GEC-FSIQ-VMI; (22) literacy-GEC-VMI-FSIQ; (23) literacy-VMI-GEC-FSIQ; (24) literacy-VMI-FSIQ-GEC.

In terms of *reading*, the model sequence analyses suggested that FSIQ accounted for the most variance, followed by literacy (i.e., the main effect of age category, handwriting fluency, and their interaction term), GEC, and VMI. The submodel order chosen for *reading* was *FSIQ-literacy-GEC-VMI.* In terms of *handwriting fluency*, the model sequence analyses suggested that literacy (i.e., reading) accounted for the most variance, followed by VMI, FSIQ, and GEC. The model sequence for *handwriting fluency* was *literacy-VMI-FSIQ-GEC.* The following regression analyses are reported based on these two submodel orders.

Reading

Prior to conducting the hierarchical regression analyses, outlier tests were conducted based on the criterion of standardised residuals exceeding ±2.0, using three outlier analyses (i.e., Mahalanobis Distance, Cook's Distance and Centred Leverage Value). No outliers were identified.

A summary of the hierarchical regression analyses with five models predicting *reading* is illustrated in Table 6a. Model 1, which included Autism Severity was significant (F (1,49) = 6.11, p =.02, R^2 = .11). Model 2, which added FSIQ was significant *(F (1, 48) = 33.73, p < .001, R^2 = .58).* The addition of FSIQ was significant and explained an additional 47% variance (ΔR^2 = .47, p < .001). Model 3, which added the main effect of age-category and handwriting fluency (Age_Cat * HF), and the interaction term (i.e., age category * handwriting fluency) was significant *(F (3, 45)* =

17.04, p < .001, R² = .65). The addition of the main effect of age-category and handwriting fluency, and interaction term was significant and explained an additional 7% variance (ΔR² = .07, *p* = .04). Model 4, which added GEC was significant *(F (1, 44) = 14.27, p < .001, R² = .66).* The addition of GEC was not significant and explained an additional 1% variance (ΔR² = .01, *p* = .38). Model 5, which considered all variables was significant (*F* (1, 43) =11.96, *p* < .001, R² = .66). The addition of VMI was not significant and explained an additional 0.02% variance (ΔR² = 0.0002, *p* = .87).

In terms of *reading*, FSIQ was found as the only predictor in this analysis (see Model 5), exhibiting a unstandardised coefficient *B* of 0.07 (*p* < .001). This suggested that for each one-point increase in FSIQ, the *reading* score increased by 0.07 units. The standardised coefficient (β) is .56, which indicated a moderate to strong effect size suggesting that FSIQ is an important factor in determining *reading* ability. This suggested that higher intelligence, as measured by FSIQ, is associated with better *reading* performance.

Table 6a. Summary of predictors for the *reading* DV using hierarchical regression.

Reading	**Model 1**				**Model 2**				**Model 3**				**Model 4**				**Model 5**			
	B (SE)	*β*	*t*	*95 % CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*
Autism Severity	* **-.32 (.13)**	-.33	-2.47	-.58, -.06	-.02 (.10)	-.02	-.15	-.22, .18	-.05 (.10)	-.05	-.50	-.25, .15	.03 (.13)	.03	.22	-.24, .29	.03 (.13)	.03	.21	-.24, .30
FSIQ					*** **.09 (.01)**	.76	7.39	.07, .11	*** **.07 (.01)**	.60	5.43	.05, .10	*** .07 (.01)	.58	5.07	.04, .10	*** **.07 (.02)**	.56	4.18	.04, .10
Age									-.82 (.49)	-.22	-1.38	-2.01, .38	-.95 (.61)	-.26	-1.55	-2.18, .28	-.96 (.62)	-.26	-1.54	-2.22, .30
Hand-writing fluency									.04 (.02)	.27	1.96	-.001, .08	.03 (.02)	.24	1.072	-.01, .07	.03 (.02)	.24	1.60	-.01, .07
Age_CatHF*									-.04 (.36)	-.02	-.10	-.76, .69	.03 (.37)	.02	.09	-.71, .78	.04 (.38)	.02	.10	-.72, .79

GEC													-.02 (.02)	-.13	-.89	-.07, .03	-.02 (.02)	-.13	-.87	-.07, .03
VMI																	.02 (.13)	.02	.16	-.25, .29
R	.33				.76				.81				.81				.81			
R²	.11				.58				.65				.66				.66			

Adjusted R²	.09	.57	.62	.61	.61
SE	1.79	1.23	1.16	1.16	1.17
∆ ***R²***	.11	.47	.07	.01	.0002
F	6.11	33.73	17.04	14.27	11.96
∆***F***	6.11	54.66	3.05	.79	.03
df1	1	1	3	1	1
df2	49	48	45	44	43

*p<.05, **p<.01, ***p<.001 *Age_Cat HF: the interaction term of the age category and handwriting fluency

Handwriting Fluency

A summary of the hierarchical regression analyses with five models predicting *handwriting fluency* is illustrated in Table 6b. Model 1, which included Age-Category and Autism Severity is significant (F (2,48) = 3.28, p=.046, R^2 = .12). Model 2, which added Reading was significant *(*F (1, 47) = 8.29*, p < .001,* R^2 = .35*).* The addition of Reading was significant and explained an additional 23% variance (ΔR^2 = 0.23, p < .001). Model 3, which added VMI was significant *(*F *(*1, 46) = 7.56*, p < .001,* R^2 = .40*).* The addition of VMI was not significant and explained an additional 5% variance (ΔR^2 = 0.05, p = .06). Model 4, which added FSIQ was significant *(F (1, 45) = 5.99, p< .001*, R^2 = .40*).* The addition of FSIQ was not significant and explained an additional 0.3% variance (ΔR^2 = 0.003, p = .63). Model 5, which considered all variables was significant (F (1, 44) =4.89, p < .001, R^2 = .40). The addition of GEC was not significant and explained an additional 0.03% variance (ΔR^2 = 0.0003, p = .89).

In terms of *handwriting fluency*, Reading was the strongest predictor in this analysis, exhibiting a high unstandardised coefficient B of 3.14 (p < .001) and indicates a moderate effect size (β = 0.44). This indicates that *reading* is a significant predictor of *handwriting fluency*. Furthermore, age-category was predictor, presenting a positive unstandardised coefficient B of 8.56 (p = .03), indicating that older children had better handwriting fluency than younger children. The effect size of age-category is low to medium (β = 0.32). Although VMI was not a predictor for *handwriting fluency*, it neared significance (p < .06). These findings emphasised the importance of considering both Reading and age-category when assessing handwriting fluency in autistic children aged 7 to 11 years old.

Table 6b. Summary of predictors on handwriting fluency using hierarchical regression.

Hand-writing fluency	**Model 1**				**Model 2**				**Model 3**				**Model 4**				**Model 5**			
	B (SE)	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*
Age-Cat	5.35 (3.68)	.20	1.45	-2.05, 12.76	** **10.44 (3.45)**	.39	3.03	3.51, 17.37	* **8.94 (3.43)**	.33	2.61	2.03, 15.85	* **8.65 (3.52)**	.32	2.46	1.67, 15.72	* **8.56 (3.61)**	.32	2.37	1.28, 15.83
Autism Severity	-1.74 (.96)	-.25	-1.81	-3.67, .19	-.24 (.92)	-.03	-.26	-2.08, 1.61	-.10 (.89)	-.01	-.11	-1.90, 1.70	-.22 (.94)	-.03	-.24	-2.11, 1.67	-.10 (1.26)	-.02	-.08	-2.64, 2.43
Reading					*** **3.91 (.97)**	.54	4.03	1.96, 5.86	* **2.81 (1.10)**	.39	2.56	.60, 5.02	* **3.17 (1.34)**	.44	2.37	.48, 5.87	* **3.14 (1.37)**	.44	2.30	.39, 5.90
VMI									2.11 (1.08)	.27	1.96	-.06, 4.28	2.36 (1.20)	.31	1.96	-.06, 4.79	2.35 (1.22)	.31	1.93	-.11, 4.81
FSIQ													-.09 (.18)	-.10	-.49	-.44, .27	-.09 (.18)	-.10	-.49	-.45, .27
GEC																	-.03 (.21)	-.03	-.14	-.46, .40

R	.35	.59	.63	.63	.63

R²	.12	.35	.40	.40	.40
Adjusted R²	.08	.30	.34	.33	.32
SE	12.91	11.24	10.92	11.01	11.13
∆ R²	.12	.23	.05	.003	.0003
F	3.28	8.29	7.56	5.99	4.89
∆F	3.28	16.24	3.84	.24	.02
df1	2	1	1	1	1
df2	48	47	46	45	44

*p<.05 **p<.01 ***p<.001

Discussion

The present study investigated whether VMI was associated with literacy skills and to what extent VMI variables, along with demographic (i.e., age), autism severity and cognitive (i.e., FSIQ and executive function) variables, predicted literacy skills (i.e., reading; handwriting skills) in autistic children aged 7 to 11 years old.

The bivariate correlation analyses showed that VMI in autistic children was positively correlated with *reading* and *handwriting skills*, which is consistent with previous findings that have showed similar relationships in non-autistic children (Brock et al., 2018; Cameron et al., 2012, 2015; Carlson et al., 2013; Hopkins et al., 2019; Longcamp et al., 2016; Volman et al., 2006). For example, Brock et al. (2018) and Cameron et al. (2012), who focused on early years non-autistic children, found that VMI was positively associated with reading and other school readiness skills (e.g., maths) and they suggested that VMI was an important consideration on in early childhood learning. Furthermore, Carlson et al. (2013) and Hopkins et al. (2019) extended these observations to from a developmental perspective and showed that children aged 7 to 10 years showed positive relationships between VMI on *word reading* and *reading comprehension*. To read words successfully, a child must be able to visually differentiate printed letters and words, convert them into phonological codes (Baddeley et al., 2009), and accurately recognise these words in reading tasks. Decoding skills are fundamental for developing word reading abilities and play a crucial role in enhancing overall reading comprehension (Hoover & Gough, 1990). In terms of handwriting, it was suggested that VMI is fundamental for handwriting skills (Longcamp et al., 2016; Volman et al., 2006) as they both engage visual and motor

processing operations. Handwriting specifically enhances pattern recognition, thereby improving the fluent recall of letters and words during reading (Waterman et al., 2014). Thus, VMI influences both reading and handwriting skills, which is consistent the current findings in autistic children. Moreover, the present findings indicated that reading was significantly associated with handwriting and suggests a reciprocal relationship between reading and handwriting whereby proficiency in handwriting underpins fluency in letter and word identification, plus reading comprehension (see Abbott et al., 2010).

Although the analyses showed that VMI was significantly correlated to *reading* and *handwriting fluency*, the follow-up hierarchical regression analysis showed that FSIQ is the only significant predictor for *reading* (i.e., word reading and reading comprehension). This finding is consistent with previous studies (Christopher et al., 2012; Cutting & Scarborough, 2006; Mayes et al., 2007) on the importance of FSIQ in reading. For example, Christopher et al. (2012) found that FSIQ significantly predicted both word reading and reading comprehension, compared to other cognitive factors such as working memory and inhibition. Moreover, they found that FSIQ was more predictive of reading comprehension and word reading, which suggests that word reading and reading comprehension has different mechanisms, and this could relate to the general intelligence (Christopher et al., 2012). Mayes et al. (2007) ran regression analysis and found that FSIQ was the strongest predictor of academic achievement, including reading and maths.

Although VMI is not a significant predictor to *reading*, VMI was significantly correlated with FSIQ, suggesting that the two variables may have mediating effects

that corresponds to the variance in reading that is explained by the overlap between VMI and FSIQ (MacKinnon, 2008; Preacher & Kelley, 2011). Gonzalez et al. (2007) found that IQ was significantly higher in normal compared to low VMI autistic children aged 4 to 10 years old. This effect also found in autistic adolescents aged 3 –16 years old (Ramos-Sánchez et al., 2021). A systematic review conducted by Van der Fels (2015) suggested that motor skills have correlations with cognitive skills. Therefore, a mediation analysis between VMI and FSIQ, using structural equation modelling, could offer further insights the variables that influence *reading* skills in autism.

In terms of *handwriting fluency*, the hierarchical regression analyses showed that *age-category* (younger vs older autistic children) and *reading* were significant predictors. These effects are consistent with previous studies (Frolek Clark & Luze, 2014; Hellinckx et al., 2013) and specifically a study by Hellinckx et al. (2013) that conducted a hierarchical regression to examine predictors of handwriting quality and speed in autistic children aged 7 – 12 years old. They showed that age was the strongest predictor of handwriting fluency and quality in both autistic and non-autistic children aged 7 to 12 years old. Taken together, it is therefore likely that the *handwriting fluency* age effect shown in Study 2 indicated that writing performance is enhanced across development and learning (Rueckriegel et al., 2009), which is consistent with the suggestion that the increased volume of formal handwriting instructions and practice influences performance (Beery et al., 2004; Marr et al., 2003). Although reading was also enhanced by consistent individual instructional practices and combinations of practices (Duke & Pearson, 2021), the complexities of reading, such as comprehension and critical thinking (Paige et al., 2024), can lead to variable reading

outcomes. For example, students' prior knowledge and experience may affect their reading comprehension (Smith, 2021). Factors (e.g., variability in comprehension, focus level and engagement level) can influence reading development, making it less predictable than handwriting improvements (Connor et al., 2009; Graham et al., 2018).

The fact that *reading* also predicted *handwriting fluency* was interesting as it builds on previous work (Frolek Clark & Luze, 2014) that found that 5 to 6 years old children in the reading at-risk group scored lower in handwriting performance, VMI skills, and fine motor measures. In the Frolek Clark & Luze (2014) study, however, VMI predicted handwriting in children aged 5 to 6 years old, which is aligned with similar VMI effects for children aged 7 to 8 years old (see Volman et al., 2006). Although VMI was not a significant predictor for *handwriting fluency*, the regression analysis indicated the effect was close to significance (p = .06) of VMI predicting handwriting. Therefore, younger children may show a greater contribution of VMI skills in early handwriting because their fine motor control is still developing, and the children rely on fine motor control more at a younger age. The reliance of children on fine motor control show that the importance of VMI in early handwriting. Moreover, Berninger et al. (1992) suggested that in primary school, children's ability to automatically produce the letters of the alphabet, rapidly code orthographic information, and to execute sequential finger movements significantly influences the handwriting performance of children completing a copying task. As children's skills continue to develop over time, children are also required to improve the ability to write letters and complete more complex writing tasks – such as the production of complete and meaningful sentences – and these processes require a more integrated knowledge system including the symbolic nature of letters, comprehension of the knowledge, and knowledge of writing

conventions (Puranik & Lonigan, 2011). This could therefore be a reason why word reading and reading comprehension was the strongest predictor of *handwriting fluency* in autistic children aged 7 to 11 years old in the current study.

Implications for autistic literacy studies and practice

The findings of Study 2 have implications for school practices aimed at improving reading and writing skills in autistic children aged 7 to 11 years old. Although there was a positive correlation between VMI and *reading* skills, FSIQ is the only predictor for reading skills in autistic children aged 7 to 11 years old. Reading activities can be designed to not only improve literacy but also to boost overall cognitive levels. For instance, structured reading exercises that emphasise visual differentiation of letters and words and the conversion of visual stimuli into phonological codes can aid in the development of decoding skills (Baddeley et al., 2009). These processes, involving working memory, attention and planning, are crucial for word reading and contribute significantly to overall reading comprehension, fostering a cognitive development for children in Key Stage 2 (Sesma et al.,2009).

The present study also highlights the reciprocal relationship between reading and writing, indicating that enhancements in one area can positively impact the other. Handwriting fluency and quality, for instance, can be significantly improved through targeted reading exercises. By engaging autistic children in activities that emphasize text understanding and interpretation, educators can enhance their ability to recognise the word pattern, more accurately recall and write letters and words (Waterman et al., 2014). As reading comprehension improves, children become more familiar with the patterns and structures of written language, which in turn, boosts handwriting

performance. This integrated approach promotes simultaneous development of both reading and writing skills, with each reinforcing the other.

Furthermore, the study highlights the importance of tailored interventions that consider autistic children's reading and handwriting skills. Practices should include more focused exercises on word recognition and comprehension, recognizing the significant role these skills play in both reading and handwriting. By implementing targeted reading comprehension exercises, educators can improve handwriting quality and fluency. Enhancing reading skills through comprehension practice not only supports better handwriting but also strengthens overall literacy. This dual focus on reading and writing ensures a comprehensive strategy that addresses the interconnected nature of these essential skills in autistic children aged 7 to 11 years old. Additionally, the significant predictor role of FSIQ in reading skills suggests that cognitive assessments should inform intervention strategies, ensuring that they are appropriately challenging and supportive.

Study Imitation

This study acknowledges several limitations. Firstly, the inclusion of nonverbal children in the sample was driven by referrals from educational institutions, reflecting a commitment to inclusivity and ensuring representation across diverse cognitive profiles. Nonetheless, nonverbal children were excluded in the main analysis of correlation and regression. Future research could adopt a more focused approach, specifically targeting nonverbal autistic children to comprehensively address their distinct literacy needs and challenges, thereby refining interventions tailored to their requirements. Additionally, while our sample size was adequate for certain analyses,

it may have been insufficient for robust regression analyses. Expanding the sample size in subsequent research would enhance statistical power and foster the reliability of results, facilitating more precise conclusions.

Furthermore, although this study employed regression analysis to investigate predictive relationships, the complexity of interrelated variables suggests the utility of advanced methodologies such as structural equation modelling (SEM). SEM enables an exploration of mediating pathways between FSIQ, VMI and executive function and literacy skills, offering deeper insights into the mechanisms underlying literacy outcomes in autistic children. To broaden the scope of inquiry, future investigations could incorporate additional literacy variables (e.g., spelling) to capture a comprehensive spectrum of literacy skills. For example, spelling is linked to phonological awareness (i.e., the ability to recognise sounds in language), and orthographic knowledge (i.e., the structure of letter patterns and word structures) (Moats, 2005). These skills are both essential to decode and recognise words, to support reading and writing. By addressing these limitations, future research can build upon our findings, refining interventions and advancing knowledge to effectively support the literacy development of autistic children aged 7 to 11 years old.

Conclusion

This study highlights the significant roles of FSIQ and age in predicting literacy skills, specifically *reading* and *handwriting fluency*, in autistic children aged 7 to 11 years old. While VMI is positively correlated with literacy skills, FSIQ emerged as the sole significant predictor for reading, emphasizing its critical influence. Age and reading ability were key predictors of *handwriting fluency*, indicating the developmental

nature of these skills and their interrelation. These findings emphasise the importance of enhancing cognitive abilities and integrating reading and handwriting exercises to support literacy development in autistic children. Future research should address these opportunities and explore the mediating pathways to provide a more comprehensive understanding of these relationships.

Chapter 5. Visuomotor Control and Predictors of Literacy Skills in Children aged 7 to 11 years old.

Introduction

This chapter extended the findings from Chapter 4, which examined visuomotor integration and literacy skills in autistic children aged 7 to 11 years old using standardised measures. Nonetheless, Chapter 4 did not address whether nonautistic children within the same age range would have similar predictors for literacy skills. The systematic review in Chapter 3 revealed differences in visuomotor control and learning between autistic and non-autistic individuals. Movement outcomes and production measures, such as movement time, total error, and kinematic markers, highlighted the underlying motor mechanisms that differentiate autistic from nonautistic individuals. Therefore, the aim of this chapter was to fill these gaps by investigating whether there were any visuomotor control differences between autistic and non-autistic children aged 7 to 11 years old using movement outcomes and production measures. Additionally, it seeked to identify the predictors of literacy skills in this age group, providing a comprehensive understanding of these factors across both autistic and non-autistic children.

To build upon previous studies employing standardised motor measurements [e.g., Beery motor assessment tool (Beery VMI, 2010)], kinematic analysis had been used to determine whether specific movement characteristics (e.g., peak velocity or time to peak velocity) to understand the underlying VMI mechanism (Foster et al., 2023; Hayes et al., 2016; Wild et al., 2012). In a study by Foster et al. (2023), participants watched pre-recorded videos featuring a single white dot moved along a horizontal

trajectory, then imitated the movement on a tablet. The results indicated that peak velocity occurred earlier in post-test compared to the baseline in both autistic and non-autistic children. Additionally, both groups showed the similar error and learning trajectory when learning imitating the atypical sequence. These findings aligned with Prinz's (1997) perception-action matching mechanism, suggesting nonautistic individuals typically employ visual-motor integration processes to incorporate visual information into action plans. The successful reproduction of observed atypical kinematics by the autism children in the post-test indicated that similar VMI processes were operational in autism, as supported by previous research (Cook et al., 2013; Foster et al., 2020a). Kinematic markers (e.g., peak velocity) implied that when imitating observed atypical kinematics, autistic movement profiles resembled with non-autistic individuals following observational practice without social cues. This challenged the notion of a widespread problem in the brain's ability to observe and imitate actions in autism. Thus, it has been important to consider kinematic analysis in understanding VMI mechanisms.

The current chapter examined visuomotor control differences between autistic and non-autistic children aged 7 to 11 years old using kinematic analysis and other movement outcomes and production measures (e.g., movement time). Similar to Chapter 4, VMI, cognitive measures (i.e., full-scale IQ and executive function), and demographic variables were used in correlation and regression analysis on literacy skills (i.e., word reading, reading comprehension, and handwriting fluency). Additionally, movement outcomes and production measures were utilized to analyse the underlying VMI mechanisms in both autistic and non-autistic children aged 7 to 11 years old. The choice of specific movement outcomes and production measures was

based on previous literature on visuomotor planning markers (i.e., peak velocity and percentage time to peak velocity) and visuomotor performance markers (i.e., movement time and production error), as well as the findings of the mean differences test between autistic and non-autistic children aged 7 to 11 years old in this chapter. The research questions were:

1. Are there any visuomotor differences between autistic and non-autistic children aged 7 to 11 years old?

   It is hypothesised that autistic children have longer movement time, more symbol production error, lower peak velocity, more percentage time to peak velocity, and more variability of movement time, symbol production error, peak velocity, and percentage time to peak velocity for all symbols in copying and tracing tasks than non-autistic children aged 7 to 11 years old.

2. What are the predictors of literacy skills in children aged 7 to 11 years old?

   It is hypothesised that age, kinematic markers (e.g., peak velocity and percentage time to peak velocity) and full-scale IQ are predictors (see Arán Filippetti & Richaud, 2015; Carlson et al., 2013) of literacy skills in children aged 7 to 11 years old.

Methods

Power analysis / Sample size

A power analysis G*Power (Faul et al., 2007) was used to determine a minimum sample size for the study. The goal was to obtain .95 power to detect a large effect size of .80 at the standard .05 alpha error probability. The software G*Power indicated a sample size of 155 was required when conducting a mixed design ANOVA, and a sample size of 25 was required when conducting multivariate regression analysis. Based on previous studies, this n was also typical when using lab-based tasks with autism groups (Foster et al., 2020a, 2020b; Glazebrook et al., 2009; Hayes et al., 2018).

Participants and Recruitment Process

Sixty-one children were recruited from 4 autism special schools and 1 mainstream school in London (see Table 7; NB, the 32 autistic children were from Chapter 3). Chi-square tests were performed to examine differences in the categorical data (i.e., gender, whether English as their first language) for the autistic and non-autistic participants. Fisher's exact test was applied if the assumptions were violated (i.e., the assumption of chi-square is that no more than 20% of cells have frequencies <5). The nonautistic children were recruited based on the following inclusion criteria: (1) aged 7 and 11 years old in Key stage 2; (2) did not have a neurological condition, such as autism spectrum disorder or Down syndrome; (3) children could understand verbal instructions and perform pen/paper/tablet copying and tracing activities (i.e., copying and tracing a straight line using a pen).

For the recruitment processes and following a period of 6 months familiarisation within schools, and as per Chapter 4, I worked with teaching staff (e.g., head teacher, assistant headteacher, or research lead) of the new mainstream school to contact parents/caregivers who met the inclusion criteria. Following contact, a participant information sheet and consent form were sent to the parents/caregivers to explain the aims of the study, the activities that their child/children would engage within the study, and information on how and whether to volunteer. Ethics was received and approved by IOE, Faculty of Education and Society, University College London, with data protection No. Z6364106 on 18th February 2023.

Table 7. Mean Differences of Demographic Information between Autistic and Non-autistic Participants

Domain	Autism	Non-Autism	X^2/t	*p*
Participant	N = 32	N = 29		
Gender	M = 25 F = 7	M = 15 F = 14	$X^2(1) = 4.70$	.03
English as first language	Yes = 22 No = 10	Yes = 25 No = 4	$X^2(1) = 2.62$	.11
Age	10.35 (1.22)	9.32 (0.89)	t (59) = 2.17	<.001

Materials

The standardised measurements were identical to those used in Chapter 4

[i.e., intelligence quotient (IQ), executive function (EF), VMI and literacy measures]. Two additional BeeryKin VMI tasks were developed to measure and quantify the underlying sensorimotor mechanisms engaged during the copying and tracing activities.

Adapted BeeryKin VMI Task - Copy Task Materials

The task was a new VMI protocol that was developed from the Beery Buktenica Developmental Test of Visual-Motor Integration (Beery VMI; Beery & Beery., 2010). The Beery VMI copy task was used as it one of most often used measures of VMI (Khatib et al., 2020). Specifically, the copying figures task had been the most common task to measure VMI, as it had been used to assess the fidelity of the integration of visual information processing and motor coordination (Beery & Beery, 2010). The new BeeryKin VMI protocol consisted of 3 symbols (i.e., left oblique line, oblique cross (an “X” shape) and triangle) selected from the standardised Beery VMI measure. The symbols were chosen to examine differences in motor planning (i.e., left oblique line with 1 motor planning position, and oblique cross with 2 motor planning positions) using kinematic analysis, reflecting the underlying sensorimotor control processes. The protocol was developed based on pilot work performed in autism special schools.

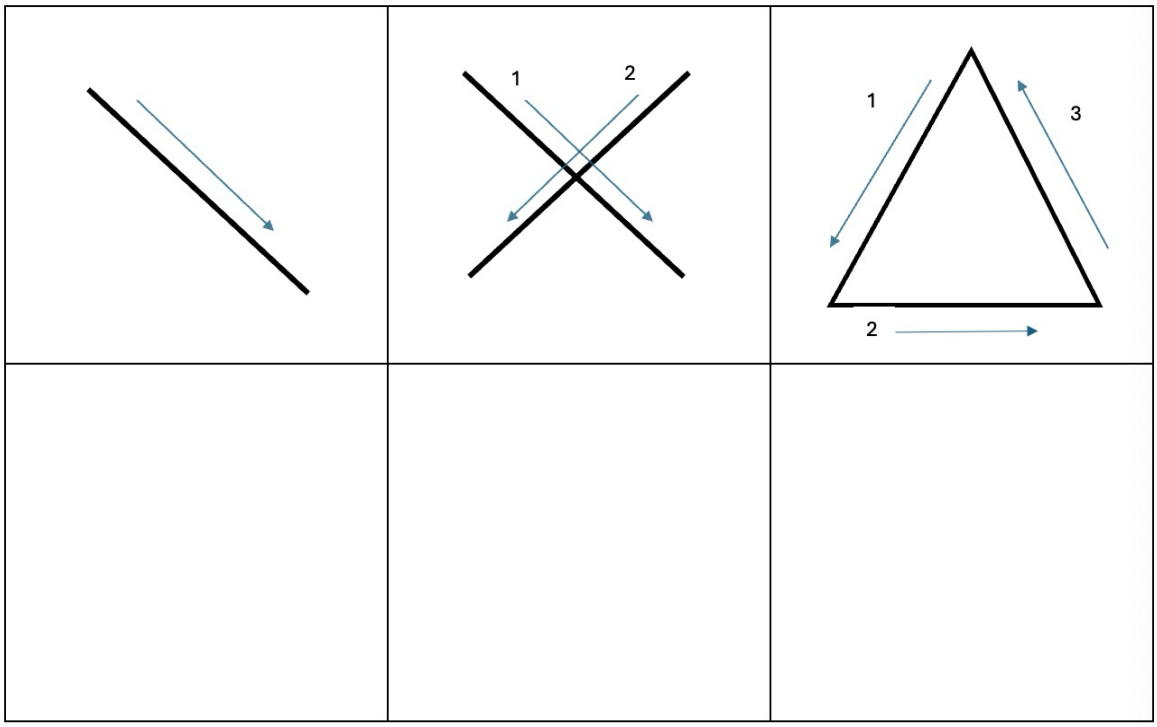

Figure 4. Illustrations of Copy Task Materials

Adapted BeeryKin VMC Task - Tracing Task Materials

The task was a new VMC protocol that had been developed from the Beery Buktenica Developmental Test of Visual-Motor Integration subtest on motor coordination (Beery VMC; Beery & Beery, 2010). The motor coordination test (i.e., tracing task) was selected as it has been consistently used to measure children's fine motor control abilities (Beery & Beery, 2010). As per the BeeryKin VMI protocol, the BeeryKin VMC protocol consisted of the same 3 symbols (i.e., left oblique line, oblique cross (an "X" shape) and triangle) selected from the Beery VMC motor coordination subtest. The symbols were chosen to examine differences in motor planning (i.e., left oblique line with 1 motor planning position, oblique cross with 2 motor planning positions) using kinematic analysis.

The new BeeryKin method was coded in MATLAB using Psychtoolbox. The task was developed from the two Beery-Buktenica Developmental Test of VisualMotor Integration and Coordination subtests. Rather than the symbols being presented within a standardised workbook where children used a pencil to trace or copy symbols, the symbols were presented graphically on the screen of a Wacom Cintiq Pro 24, which had a sampling rate of 120hz. The symbols were scaled and positioned to the exact dimensions of the standardised Beery task. The BeeryKin symbols were the left oblique line, oblique cross (an “X” shape) and a triangle]. Each child was required to copy 5 trials for each shape (15 trials in total) and traced 5 trials for each shape (15 trials in total). The trials were randomised for each participant to control for order-effects. Based on the Beery standardised measure, the children were instructed to copy and trace the symbols as fast and accurately as possible. For the one segment line was at 45-degree angle. For the cross, both left and right oblique lines was at 45-degree angle and children completed two movement segments. For the triangle at 60-degree angle, children completed three movement segments. Please see Figure 4 (copy task materials) and Figure 5 (trace task materials) for their copying and tracing starting points and directions.

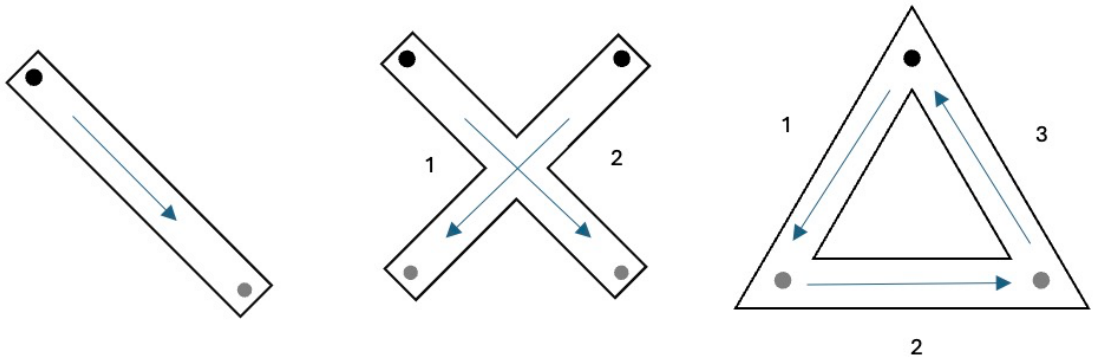

Figure 4. Illustrations of Task Materials

Measured Variables

The measured variables of IQ, EF, VMI paper assessment, and literacy were identical to those used in Chapter 4. From the new BeeryKin measure, VMI performance and planning markers from the children's copying and tracing activities were selected. Based on the model of Multiple-Process Model of Limb Control (Elliott et al., 2010), the following specific kinematic markers were measured to quantify the movement execution and underlying motor control processes:

VMI performance:

Movement time (MT) and MTsd. Movement time represented the overall duration between the initiation (start) and completion (end) of each copying or tracing movement performed for each symbol. Movement time standard deviation allows to explore the variability of the movement in terms of its timing.

Symbol Production Error (SPE) and SPEsd. Symbol production error represented the error in area for each individual symbol. The first step of symbol production error calculation process was to generate a bounding box around each symbol using a MATLAB function. Subsequently, the standard symbol area score was determined by multiplying the width and height of the bounding box for each standard symbol. Following this, the symbol area of the produced symbols was imputed by multiplying the width and height of the corresponding bounding box. In the final step, the letter production errors were calculated by subtracting a child's produced symbol area from the standard symbol area score. Symbol production error standard deviation allows to explore the variability of the movement in terms of its accuracy.

***VMI Planning*:**

In terms of motor planning, the segment of movement of left oblique line, and the first segment of movement of the cross (i.e., a left oblique line at 45-degree angle) were analysed. The two segments were chosen as they were identical in dimension and the direction in which the copying and tracing movements were performed. The segments and symbols were chosen to examine differences in motor planning (i.e., left oblique line with 1 motor planning position, and oblique cross with 2 motor planning positions) using kinematic analysis.

Peak Velocity (PV) and PVsd. Peak velocity was selected as it represented the maximum speed achieved during copying and tracing of symbols. This marker offers an insight into sensorimotor planning and control processes (Elliott et al., 2010). Peak velocity standard deviation allows to explore the variability of the planning of the movement.

Percentage Time to Peak Velocity (%TTPV) and %TTPVsd. Time for peak velocity represented the specific time when the velocity reached its highest point during copying or tracing of symbols. This marker offers an insight into sensorimotor planning and control processes (Elliott et al., 2010). Percentage time to peak velocity standard deviation allows to explore the variability of the planning of the movement.

Procedure

All children who volunteered for the study performed the activities within their own school. I first received permission from the school headteachers to pilot-test the measurement activities with several children to refine the process. On each testing

day, I first spent time (~30 mins) in a class to familiarise herself with the teaching staff and children. She then worked with the teaching staff to ask each child whether and when they would like to take part in the study. After agreeing to take part in the study, each child individually moved to a small room located within the classroom where the measurement activity was set-up on a small table next to a chair. Each child was invited to sit at the table and then received task instructions from me on how to perform each specific measurement. The child was asked to confirm they understood the instructions, and if needed, they were provided with additional prompts to clarify the process. Based on pilot testing, each measurement was performed separately and only one measurement activity was located at the table to promote attention on task. The 6 activities (Beery VMI; BeeryKin, BAS-3; YARC; DASH; WASI) were performed in a randomised order and I followed the specified instructions from each standardised manual. On average, the total time to complete the 5 tasks was 2 hours per child and these tasks were performed on separate days at each school. The tasks were: 1) copying and tracing activities based on Beery VMI (e.g., copying and tracing a line using a pen/pencil); 2) BeeryKin activities associated with copying and tracing on a graphics tablet; 3) word reading activities based on BAS-3 (e.g., read a list of words out loud); 4) reading comprehension activities based on YARC (i.e., read two passages and answer 8 questions for each passage); 5) handwriting activities based on DASH (i.e., write lower-case alphabet letters in the order from a to z in one minute); 6) IQ-related activities based on WASI (e.g., read a word out loud and explain the meaning of this word). As stated, the parents/caregivers completed the questionnaires of CARS, SRS-2, and BRIEF and returned the forms to the classroom teacher.

Hand movement data reduction

Using a custom written MATLAB routine, the start and end of each copying and tracing movement from the x and y axis position data were recorded. The position data for each movement was processed using a low-pass 4th order autoregressive filter with an 8 Hz cut-off (Foster et al., 2018, 2020b). The filter was used to minimise measurement noise in the experimental time-series data before differentiation using a 2-point central difference algorithm to obtain velocity. To quantify movement production during copying and tracing, movement duration (MT) and symbol production error from the time-series data was extracted from each trial. Further analysis of movement kinematics was focused on the x and y axis data. A MATLAB routine extracted peak velocity and percentage-time-to-peak-hand-velocity (%TTPV) from each trial. These kinematic markers were chosen as they provided discrete measures that reflected participants sensorimotor planning and control processes (Elliott et al., 2010).

Data Analysis

Prior to analysing research question 1, a 2 (group: autistic vs non-autistic children) x 2 (task: copying vs tracing) x 2 (condition: paper vs tablet) mixed-design repeated measures ANOVA was carried out to examine whether there were any motor performance differences between Beery VMI standardised assessment and the new BeeryKin method. The BeeryKin A measure was designed based on the Beery VMI standardised assessment and consisted of 6 trials in total, including 3 symbols (i.e., left oblique line, oblique cross (an “X” shape) and triangle) in both tasks (i.e., copying and tracing). Like the Beery VMI standardised assessment, children first copied the 3 symbols in order (i.e., line, followed by cross, then triangle, 1 trial per symbol per task)

on the tablet, followed by tracing the 3 symbols in order (1 trial per symbol per task). The aim of BeeryKin A was to examine whether there were any differences between paper and digital environment when children perform the copy and trace activities.

Research Question 1: are there any visuomotor differences between autistic and non-autistic children aged 7 to 11 years old?

VMI Performance: A 2 (group: autistic vs non-autistic children) x 2 (task: copying vs tracing) x 3 (symbols: line vs cross vs triangle) mixed-design repeated measures ANOVA was used to examine differences in the motor performance measurements (i.e., MT, MTsd, SPE, SPEsd, Beery VMI & VMC). Post-hoc least significant difference (Bonferroni) tests were used to examine the pairwise comparisons between the measurements and symbol (e.g., copy: line_SPE VS cross_SPE). If data was found to have violated the assumption of sphericity, the degrees of freedom was corrected using Huynh-Feldt estimates of sphericity.

VMI Planning: A 2 (group: autistic vs non-autistic children) x 2 (task: copying vs tracing) x 2 (segment of symbols: line vs 1st segment of cross) mixed-design repeated measures ANOVA was used to examine differences in the motor planning measurements (i.e., PV, PVsd, %TTPV & %TTPVsd). Post-hoc least significant difference (Bonferroni) tests were used to examine the pairwise comparisons between the measurements and symbols (e.g., copy: line_PV vs 1st segment of cross_PV).

Research Question 2: What are the predictors of literacy skills in children aged 7 to 11 years old?

To answer the second research question, and consistent with Chapter 4, bivariate correlations and hierarchical multiple regression analysis were conducted to

1) assess the strength and direction of the relationships between individual pairs of variables; and 2) to examine whether variables [e.g., demographic information (gender, age, ethnicity, first language), IQ, EF, Beery VMI, BeeryKin] predicted autistic and non-autistic children's literacy skills (i.e., word reading, reading comprehension and handwriting) and the degree to which the variables accounted for the variance.

Bivariate Correlation. Prior to hierarchical multiple the regression analysis, bivariate correlations of demographic, cognitive, VMI, BeeryKin variables, and literacy-related dependent variables (i.e., word reading; reading comprehension; handwriting fluency) were conducted to assess the strength and direction of relationships between individual pairs of variables. These correlation analyses aimed to identify potential associations among the variables and to provide insights into the nature of interdependencies, laying the groundwork for the subsequent hierarchical multiple regression analysis.

Hierarchical Multiple Regression. The hierarchical multiple regression analysis was used to examine whether variables [e.g., demographic information (gender, age, group and first language), IQ, EF, Beery VMI] predicted children's literacy skills (i.e., word reading, reading comprehension and handwriting fluency) and the degree to which variables accounted for the variance.

Results

Participants

Participants comprised 61 children (Age: *M* = 9.86 years; *SD* = 1.18) with autistic (*n* = 32; male = 25; female = 7; Age: *M* = 10.34 years; *SD* = 1.22) or nonautistic

children (*n* = 29; male = 15; female = 14; Age: *M* = 9.33 years; *SD* = 0.89) (see Table 8). Table 8 presented the mean (SD) and significant differences for VMI, literacy, IQ and executive function (EF) measures for autistic and non-autistic children. As the table showed, autistic children were significantly different and had lower scores from non-autistic children on all VMI, literacy, IQ, and EF measures.

Table 8. Mean (SD) and significant differences for motor, literacy, IQ, and executive function measures for Autistic and Non-Autistic children.

Domain	Measure	Autistic	Non-Autistic	*t*	*p*
		N =32	N =29		
VMI Measures	VMI	80.22 (16.27)	102.38 (9.88)	t (59) = -6.35	<.001
	VMC	58.50 (13.20)	76.62 (11.87)	t (59) = -5.62	<.001
Literacy Measures	Word Reading	75.66 (8.52)	109.60 (13.87)	t (59) = -11.58	<.001
	Reading Comprehension	80.44 (8.82)	101.51 (12.30)	t (50.31) = -7.62	<.001
	Handwriting Fluency	21.78 (11.98)	39.20 (14.87)	t (59) = -5.06	<.001
IQ Measures	Performance	80.18 (15.37)	116.63 (12.80)	t (59) = -10.01	.002
	Verbal	87.86 (17.06)	102.10 (17.59)	t (59) = -3.21	<.001
	Full-scale	83.54 (13.84)	110.06 (14.68)	t (59) = -7.26	<.001
Executive Function Measures	Working Memory	58.94 (9.16)	42.35 (4.90)	t (48.31) = 8.93	<.001
	GEC	83.54 (13.84)	110.06 (14.68)	t (52.53) = 8.59	<.001

VMI (Visual-Motor Integration): A measure of the integration of visual and motor skills using Beery VMI – copy task; VMC (Visual-Motor Coordination): A measure of the fine motor coordination using visual guidance using Beery VMI – tracing task; Word Reading: a measure of single-word recognition using BAS word reading subtest; Reading Comprehension: a measure of paragraph reading comprehension using YARC; Handwriting Fluency: the number of accurate lower-case in sequence alphabet letters from DASH alphabet task. Performance and Verbal IQ: a measure of performance and verbal IQ using WASI; FSIQ (Full-Scale IQ): A composite verbal and performance IQ score from WASI cognitive testing; Working memory: scores of working memory components using BRIEF. GEC (Global Executive Composite): A measure from the Behaviour Rating Inventory of Executive Function (BRIEF) that assesses executive functioning abilities

Research Question 1: are there visuomotor differences between autistic and non-autistic children aged 7 to 11 years old?

VMI Performance.

Movement Time (MT). ANOVA revealed a significant main effect of *task F (*1, 57) = 270.08, $p < 0.001$, $\eta_p^2 = 0.83$ and *symbol F* (1.85, 105.25) = 385.77, $p < .001$, $\eta_p^2 = 0.87$. As illustrated in Table 9, children performed the copying task with a shorter MT than the tracing task (a difference of 1002 ms). For *symbols*, children spent significantly shorter MTs when copying and tracing line than the cross (a difference of 2216 ms) and triangle (a difference of 1853 ms). Also, children spent significantly shorter MT when copying and tracing triangle than cross (a difference of 363 ms). There was a significant *task x symbol* interaction on MT *F (*2, 114) = 32.08, $p < .001$, $\eta_p^2 = 0.36$. Follow-up post hoc testing indicated children had significantly ($p < 0.05$) shorter MTs when tracing a triangle compared to a cross (difference of 443 ms), but a significantly ($p < .05$) greater MT when tracing a line (difference of 2133 ms). Although children had significantly ($ps < 0.05$) shorter MTs when copying a line compared to a cross (difference of 1857 ms) and a triangle (difference of 1573 ms), there was no significant ($p > .05$) difference in MT when copying a cross or triangle.

There were no other significant main effects and interactions ($ps > .05$).

Movement Time Standard Deviation (MTsd). ANOVA revealed significant main effects of *task F (*1, 57) = 34.61, $p < .001$, $\eta_p^2 = 0.38$ and *symbol F* (1.83, 104.07) = 36.90, $p < .001$, $\eta_p^2 = 0.39$. As illustrated in Table 9, children had significantly less MTsd when copying than tracing (a difference of 224 ms). For *symbols*, children had

significantly less MTsd when performing the line compared to cross (a difference of 360 ms) and the line compared to triangle (a difference of 221 ms). Also, children had significantly greater MTsd when performing the cross than triangle (a difference of 139 ms).

There was a significant *task x symbol* interaction F (1.83, 104.04) = 4.69, p = .013, η_p^2 = 0.08 that showed there were no task differences on MTsd when children performed line movements (*ps* > .05). Whereas children had significantly less MTsd when copying than tracing the cross (a difference of 345 ms) and triangle (a difference of 225 ms). The *task x symbol x group* was significant F (1.83, 104.04) = 4.91, p = .011, $\eta_p 2$ = 0.08. Follow-up post hoc testing indicated that the autistic group performed with significantly (p < .05) less MTsd when copying a triangle compared to tracing a triangle (difference of 288 ms), whereas there was no significant (p > .05) difference for non-autistic group. When copying a cross, the nonautistic group performed with significantly (p < .05) less MTsd compared to when they traced a cross (difference of 531 ms), whereas there was no significant (p > .05) difference for autistic group. When the autistic group copied a line, they performed with significantly (p < .05) less MTsd compared to when they copied a cross (difference of 288 ms), whereas there was no significant (p > .05) difference for nonautistic group. There were no other significant main effects and interactions (*ps* > .05).

Symbol Production Error (SPE). ANOVA revealed significant main effects of *symbol* F (1.77, 100.81) = 23.92, p < .001, η_p^2 = 0.30 and *group* F (1, 57) = 16.00, p <.001, η_p^2 = 0.22. As illustrated in Table 9, children had significantly less SPE when performing the line compared to triangle (p < .05; difference of 552 mm) and when

performing the cross than triangle ($p < .05$; difference of 608 mm). No significant difference was found between line and cross symbols ($p > .05$). The autistic children had significantly less SPE than non-autistic group ($p < .05$; difference of 272 mm).

There was a significant *task x symbol* interaction on SPE F (2, 114) = 27.13, $p < .001$, $\eta_p^2 = 0.25$. Follow-up post hoc testing indicated there were no significant (*ps* > 0.05) task differences when performing the line. Whereas children had significantly ($p < .05$) greater SPE when copying than tracing the cross symbol (difference of 868 mm). For the triangle, children had significantly ($p < .05$) less SPE when copying than tracing (difference of 549 mm). No other main effects and interaction were found significantly. There were no other significant main effects and interactions (*ps* > .05).

Symbol Production Error Standard Deviation (SPEsd). ANOVA revealed significant main effects of *task* F (1, 57) = 189.40, $p < .001$, $\eta_p^2 = 0.77$ and *group* F (1, 57) = 5.29, $p = .025$, $\eta_p^2 = 0.09$ on SPEsd. As illustrated in Table 9, children had significantly ($p < 0.05$) greater SPEsd in copying than tracing task (difference of 554 mm) and autistic children had significantly ($p < .05$) greater SPEsd than non-autistic children (difference of 102 mm). There were no other significant main effects and interactions (*ps* > .05).

VMI Planning.

Peak Velocity on X Axis (PVx1). ANOVA revealed a significant main effects of *task* F (1, 57) = 187.90, $p < .001$, $\eta_p^2 = 0.77$ and *symbol* F (1, 57) = 11.04, $p = .002$, $\eta_p^2 = 0.16$ on PVx1. As illustrated in Table 9, children had a significantly greater PVx1 in copying than tracing task (difference of 64 mm/ms) and had a

significantly (p <.05) greater PVx1 when performing the line than the cross (difference of 8 mm/ms). There were no other significant main effects and interactions (ps > .05).

Peak Velocity on X Axis Standard Deviation (PVx1sd). ANOVA revealed a significant main effect of *task* F (1, 57) = 65.06, p < .001, η_p^2 = 0.53 on PVx1sd. As illustrated in Table 9, children had a significantly (p <.05) greater PVx1sd when copying compared to tracing (difference of 13 mm/ms). There were no other significant main effects and interactions (ps > .05).

Peak Velocity on Y Axis (PVy1). ANOVA revealed a significant main effect of *task* F (1, 57) = 174.04, p < .001, η_p^2 = 0.75. As illustrated in Table 9, children had a significantly (p < .05) greater PVy1 when copying compared to tracing (a difference of 70 mm/ms). There were no other significant main effects and interactions (ps > .05).

Peak Velocity on Y Axis Standard Deviation (PVy1sd). ANOVA revealed a significant main effect of *task* F (1, 57) = 65.45, p < .001, η_p^2 = 0.54. As illustrated in Table 9, children had a significantly (p < .05) greater PVy1sd when copying compared to tracing (a difference of 13 mm/ms). There were no other significant main effects and interactions (ps > .05).

Percentage Time to Peak Velocity on X Axis (%TTPVx1). ANOVA revealed significant main effects of *task* F (1, 57) = 25.89, p < .001, η_p^2 = 0.31, *symbol* F (1, 57) = 4.12, p = .047, η_p^2 = 0.07 and *group* F (1, 57) = 5.83, p = .019, η_p^2 = 0.09. As illustrated in Table 9, %TTPVx1 occurred significantly (ps < .05) later in the movement when copying than tracing task (difference of 6%) and when performing the line compared

to the cross (difference of 2%). For group, %TTPVx1 occurred significantly (*ps* < 0.05) later in the movement for the autistic children compared to non-autistic children (difference of 4%).

There was a significant *task x group* interaction on %TTPVx1 *F (*1, 57) = 5.24, p = .026, η_p^2 = 0.08. Follow-up post hoc testing indicated there was no significant (p > .05) group difference when copying. Whereas %TTPVx1 occurred significantly (p < .05) later in the movement for the autistic children compared to non-autistic children (difference of 7%) when tracing. There were no other significant main effects and interactions (*ps* > 0.05).

Percentage Time to Peak Velocity on X Axis Standard Deviation (%TTPVx1sd). ANOVA revealed a significant main effect of *task F* (1, 57) = 67.70, p < .001, η_p^2 = 0.54. As illustrated in Table 9, children had a significantly lower %TTPVx1sd when copying compared to tracing (difference of 6%). There were no other significant main effects and interactions (*ps* > .05).

Percentage Time to Peak Velocity on Y Axis (%TTPVy1). ANOVA revealed a significant main effects of *task* F (1, 57) = 41.05, p < .001, η_p^2 = 0.42 and *group F* (1, 57) = 7.62, p = .008, η_p^2 = 0.12. As illustrated in Table 9, %TTPVy1 occurred significantly (*ps* < .05) later in the movement when copying compared to tracing (difference of 6%) and autistic children compared to non-autistic children (difference of 5%).

There was a significant *task x group* interaction on %TTPVy1 *F (*1, 57) = 10.76, p = .002, η_p^2 = 0.16. Follow-up post hoc testing indicated there was no significant (p > .05) group difference when copying. Whereas %TTPVy1 occurred significantly (p < .05) later in the movement for the autistic children compared to non-autistic children (difference of 7%) when tracing (difference of 8%). There were no other significant main effects and interactions (*ps* > 0.05).

Percentage Time to Peak Velocity on Y Axis Standard Deviation (%TTPVy1sd). ANOVA revealed a significant main effects of *task F* (1, 57) = 52.66, p < 0.001, η_p^2 = 0.48 and *group F* (1, 57) = 4.41, p = .040, η_p^2 = 0.07. As illustrated in Table 9, children had significantly lower %TTPVy1sd when copying compared to tracing (difference of 6%) and the autistic children had significantly greater %TTPVy1sd than non-autistic children (difference of 2%). There were no other significant main effects and interactions (*ps* > .05).

Table 9. Illustrates mean and (standard deviation) data for BeeryKin variables as a function of Group, Task and Symbol

Group	*DVs*	*Line*		*Cross*		*Triangle*	
	VMI Performance	***Copy***	***Trace***	***Copy***	***Trace***	***Copy***	***Trace***
Autistic	***MT (ms)***	881.51 (400.14)	1437.32 (479.07)	2531.07 (770.58)	3870.21 (1066.33)	2441.28 (926.17)	3517.74 (1257.48)
Non-Autistic		915.95 (379.39)	1511.91 (503.26)	2980.60 (972.58)	4230.35 (872.09)	2502.74 (925.49)	3697.61 (1038.14)
Autistic	***MTsd (ms)***	257.75 (276.39)	310.45 (198.67)	545.64 (475.88)	704.60 (483.44)	391.06 (324.45)	679.13 (581.36)
Non-Autistic		200.29 (226.35)	349.55 (242.52)	389.36 (312.86)	920.05 (693.03)	385.22 (314.46)	546.67 (345.86)
Autistic	***SPE (mm)***	1038.20 (894.35)	994.68 (234.17)	1134.13 (827.51)	492.18 (268.82)	1313.05 (737.15)	1793.43 (252.53)
Non-Autistic		1131.29 (877.33)	1232.21 (140.36)	1817.95 (1513.86)	726.12 (135.02)	1440.09 (890.53)	2057.44 (198.29)
Autistic	***SPEsd (mm)***	823.60 (435.28)	258.08 (197.62)	887.37 (479.66)	351.75 (362.77)	868.02 (413.03)	326.83 (155.20)
Non-Autistic		705.90 (345.28)	187.25 (109.28)	815.75 (499.34)	162.98 (64.84)	773.13 (431.16)	259.74 (134.50)
	VMI Planning						
Autistic	***PVx1 (mm/ms)***	138.97 (40.93)	75.78 (31.80)	127.99 (35.87)	68.46 (21.62)	/	/
Non-Autistic		136.79 (53.06)	63.91 (23.90)	124.58 (51.85)	60.00 (21.40)	/	/

Autistic	***PVx1sd (mm/ms)***	29.97 (15.16)	16.90 (10.05)	29.21 (11.62)	12.83 (7.08)	/	/
Non-Autistic		26.64 (17.64)	15.50 (8.29)	24.09 (14.45)	13.61 (8.05)	/	/
Autistic	***PVy1 (mm/ms)***	140.06 (53.20)	78.15(33.69)	134.53 (40.45)	71.02 (22.22)	/	/
Non-Autistic		143.17(54.62)	66.97 (26.02)	142.98 (57.57)	63.56 (21.56)	/	/
Autistic	***PVy1sd (mm/ms)***	32.84(18.85)	17.20(11.90)	29.77 (16.13)	14.57 (7.25)	/	/
Non-Autistic		24.79(16.46)	16.14(7.58)	25.51 (12.95)	14.00 (9.90)	/	/
Autistic	***%TTPVx1***	62.77 (9.77)	58.05 (11.31)	58.53 (7.87)	56.15 (11.10)	/	/
Non-Autistic		60.67 (7.80)	49.83 (11.45)	58.36 (6.78)	50.50 (9.41)	/	/
Autistic	***%TTPVx1sd***	9.10 (5.73)	13.57 (5.72)	8.39 (3.69)	14.24 (5.14)	/	/
Non-Autistic		8.58 (3.80)	13.71 (5.93)	8.38 (4.44)	15.23 (5.30)	/	/
Autistic Children	***%TTPVy1***	59.53 (7.47)	57.62 (10.28)	61.84 (8.55)	57.71 (9.72)	/	/
Non-Autistic		59.22 (7.19)	49.00 (11.33)	59.34 (5.90)	50.76 (9.14)	/	/
Autistic Children	***%TTPVy1sd***	10.29(4.56)	15.12(5.64)	10.02 (4.70)	15.67 (7.68)	/	/

Non-Autistic	7.22 (3.63)	13.15(5.94)	8.39 (4.98)	15.00 (7.09)	/	/

Research Question 2: what are the predictors of literacy skills in children aged 7 to 11 years old?

Handling Missing Data.

Missingness analyses were used for autistic and non-autistic participants (*n* = 61). Other than the WASI verbal, performance and FSIQ measures (all missing on 6.6% respectively), the missing data for all other variables were less than 5%, which was inconsequential to the overall results (Tabachnick & Fidell, 2013). WASI verbal, performance and FSIQ had no significant relationships with other variables. Additionally, Little's MCAR was performed and indicated that missing data was random ($\chi 2$ (109) = 109.26, *p* = .48). A multiple imputation (MI) mechanism was used for data that were missing completely at random or missing at random. Also, MI accommodated auxiliary variables (i.e. variables not containing missing data) in the imputation model to account for any patterns or relationships between these variables and the missingness of the data (Huges et al., 2019). The data set after MI were used for further analysis.

Age

Exploration of the age of participants indicated variation in the number of participants age categories (e.g., 7-8: *n* = 2; 11+: *n* = 16), and as such may influence the outcome of the overall regression analyses. Based on the previous literature (Zhang et al., 2017), participants were separated into two age groups: (1) less than 10 (<=9 yrs, *n* = 33); (2) more than and equal to 10 (>=10 yrs, *n* = 28). In this case, both age groups had similar numbers of participants and thus were added to the following analyses. The age variable was treated as a categorical variable using

‘dummy variable’ in SPSS, called age category variable, with participants less than and equal to 9 (<=9 yrs) coded as “0”, and participants more than and equal to 10 (>=10 yrs) coded as “1”. Dummy variables were used to replace the encoded categorical variables to some numeric values (generally represented by 0 and 1), so that the encoded categorical values could not have any impact on the prediction.

BeeryKin Dependent Variables.

To represent the underlying motor mechanisms of copying and tracing activities, and based on the previous literature (e.g., Foster et al., 2020a; Hayes et al., 2016, 2018), two independent variables were selected for the analysis: 1) SPE_mean, a VMI performance marker; 2) %TTPV_mean, a VMI planning marker. Note, a composite score representing %TTPV from the two axes, %TTPVx1 and %TTPVy1, was created by averaging the two data streams.

Composite Score for Measures.

Composite scores were computed for some measures as they had similar underlying common constructs (e.g., VMI and VMC) based on theoretical understanding and the outcome (see below) of bivariate correlation analysis (Raykov et al., 2016). Z-scores were used to described in the same units for all included measurements (Andrade, 2021). A new composite score (by adding z-score of each measure) was used in the regression analysis. Given the significant high value correlations between 1) word reading and reading comprehension (r = .82); 2) VMI and VMC (r = .64), composite scores were computed to represent *reading* and *VMI* domains.

Bivariate Correlation.

The two dependent variables for literacy are *reading* and *handwriting fluency*. Prior to hierarchical multiple regression analyses, bivariate correlations between independent variables, including demographic, cognitive, VMI variables (e.g., age category, FSIQ and VMI composite scores), BeeryKin variables (i.e., SPE and %TTPV), and dependent variables, including *reading* composite scores (i.e., word reading and reading comprehension) and *handwriting fluency* were conducted to assess the strength and direction of relationships between individual pairs of variables. Predictors for the regression analysis were selected based on an apriori theoretical rationale and significant correlations.

As illustrated in Table 10, the predicting variables that were significantly correlated with the dependent variables (i.e., reading and handwriting) formed the basis of the regression model. In terms of *reading*, the correlated and predicting variables for the regression analysis were group (r = .81), GEC (r = -.71), FSIQ (r = .79), VMI (r = .66), SPE (r = .26), %TTPV (r = -.26) and *handwriting fluency* (r = .59). In terms of *handwriting fluency*, the correlated and predicting variables for the regression analysis were group (r = .55), GEC (r = -.44), FSIQ (r = .57), VMI (r = .53), %TTPV (r = -.35) and *reading* (r = .59). Although SPE was not significantly correlated with *handwriting fluency*, it was added to regression analysis as a VMI performance marker to examine the predictive value to literacy (i.e., handwriting).

Table 10. Bivariate Correlations for Demographic, Cognitive, VMI, BeeryKin Variables, Reading and Handwriting Fluency.

	1	2	3	4	5	6	7	8	9	10	11
1. Reading	--										
2. Group	.81**	--									
3. Gender	.14	.28*	--								
4. Age Category	-.23	-.28*	-.18	--							
5. English as first language	-.07	-.21	.02	.12	--						
6. FSIQ	.79**	.69**	.21	-.17	-.26*	--					
7. GEC	-.71**	-.74**	-.20	.09	.10	-.63**	--				
8. VMI	.66**	.68**	.22	-.14	-.14	.76**	-.56**	--			
9. SPE	.26*	.34**	.03	.01	-.02	.13	-.33*	.07	--		
10. %TTPV	-.26*	-.26*	-.16	-.11	.16*	-.37**	.13	-.28*	.01	--	
11. Handwriting fluency	.59**	.55**	.17	.14	-.14	.57**	-.44**	.53**	.23	-.35**	--

*p < .05; **p < .01; Reading: reading composite score of YARC reading comprehension and BAS word reading reflecting reading proficiency; Gender: Participant's gender; Age_Cat: Age Category, coded as 0 = younger group, 1 for older group; English as First Language: whether participant speaks English as their first language (1 = Yes, 2 = No); Autism Severity: composite score of SRS and CARS measuring the severity of autism symptoms; GEC (Global Executive Composite): A measure from the Behaviour Rating Inventory of Executive Function (BRIEF) that assesses executive functioning abilities; FSIQ (Full-Scale IQ): A composite verbal and performance IQ score from WASI cognitive testing; VMI (Visual-Motor Integration): A composite score of visuomotor integration and visuomotor coordination using Beery VMI & VMC; SPE: Symbol production error represented the error in area for each individual symbol; %TTPV: Time for peak velocity represented the specific time when the velocity reached its highest point during copying or tracing of symbols. Handwriting Fluency: the number of accurate lower-case in sequence alphabet letters from DASH alphabet task.

Handwriting Fluency and Age Category as Interaction Term

As per Chapter 4, and because the DASH standardised measure is only age normed to children aged between 9 – 16 years of age, raw scores were used in the analysis because there were 13 children younger than age 9 years. Therefore, to ensure that age was accounted for in the DASH analysis as per all other standardised measures, an interaction term was applied to the regression model. Thus, a new variable was computed to represent the interactive effect of age and the variable for *handwriting fluency*. As the age-category variable represented age, the main effect of age-category, *handwriting fluency*, and the interaction term (i.e., age category * handwriting fluency) were used in the regression analysis for *reading*. In terms of *handwriting fluency*, age-category was entered into the regression model as it is the only variable that does not account for age.

Data Screening for Hierarchical Regression

To run the analyses, the raw data were first screened to establish if the assumptions of hierarchical regression were violated. The following tests did not reveal any violations: 1) independence of residuals (Durbin–Watson statistic of 1.99 (DV: reading); 1.58 (DV: handwriting)), 2) multivariate outliers/influential data points, 3) multicollinearity and 4) normality of residuals. As this regression was an extension to Chapter 4, the same variables were analysed: FSIQ (representing IQ variable) and executive function total scores (GEC, representing EF variable).

Hierarchical Multiple Regression

Hierarchical regression was conducted to explore predictors (e.g., age category, VMI, and BeeryKin) of *reading* and *handwriting fluency* (DVs) of children aged 7 to 11

years old. Various IVs (i.e., demographic information, FSIQ, EF, VMI, BeeryKin; literacy-related variables) were added in different model orders to examine which IV accounted for the greatest variance for a DV.

Consistent with Chapter 4, to examine the effect of different variables (e.g., age category, VMI and BeeryKin) and which submodel accounted for the most variance within each dependent variable, the submodels were examined in different orders using hierarchical regression. For *reading*, the main effect of age-category, *handwriting fluency* and their interaction term was added to the model. For *handwriting fluency*, reading was added as an IV in a model. As the sample size for the autistic (*n* = 31) and non-autistic (*n* = 28) groups were small for regression, *group* was added as the last submodel (model 6/7) in the regression model. In this case, group was not accounted for in other variables before being entered as the final submodel. For *handwriting fluency*, age category was as a control variable and added as model 1. Five submodels (i.e., IQ, EF, VMI, BeeryKin, literacy-related variables) were tested in across 32 different permutations. The model sequence testing was the same as in Chapter 4.

In terms of *reading*, the model sequence analyses suggested that based on the R^2 (the proportion of the variance for DV), the submodel order (from highest R^2 to lowest) was: *FSIQ-GEC-literacy (main effect + interaction)-BeeryKin-VMI-Group*. For *handwriting fluency*, the submodel order was *literacy-VMI-BeeryKin-FSIQ-GEC-Group.* The following regression analyses are reported based on this order.

Reading

Prior to conducting the hierarchical regression analysis, outliers were identified based on the criterion of standardised residuals exceeding ±2.0, using three outlier analysis (i.e., Mahalanobis Distance, Cook's Distance and Centred Leverage Value). No outliers were identified.

A summary of the hierarchical regression analyses with six models predicting *reading* is illustrated in Table 11a. Model 1, which included FSIQ was significant (F (1,59) = 98.71, $p < .001$, $R^2 = .63$). Model 2, which included GEC was significant *(F (1, 58) = 67.15, $p < .001$,* $R^2 = .70$*).* The addition of GEC was significant and explained an additional 7% variance ($\Delta R^2 = 0.07$, $p < .001$). Model 3, which included the main effect of age-category and *handwriting fluency*, and the interaction term (i.e., age category * handwriting fluency) was significant *(F (3, 55) = 31.52, $p < .001$,* $R^2 = .74$*).* The addition of the main effect of age-category and *handwriting fluency*, and the interaction term was significant and explained an additional 4% variance ($\Delta R^2 = 0.04$, $p = .04$). Model 4, which included BeeryKin variables was significant *(F (2, 53) = 22.01, $p < .001$, $R^2 = .74$).* The addition of BeeryKin variables was not significant and explained an additional 0.3% variance ($\Delta R^2 = 0.003$, $p = .75$). Model 5, which included VMI was significant *(F (1, 52) = 18.95, $p < .001$, $R^2 = .75$).* The addition of VMI was not significant and explained an additional 0.1% variance ($\Delta R^2 = 0.001$, $p = .75$). Model 6, which considered all variables was significant (including group) was significant (F (1, 51) = 20.15, $p < .001$, $R^2 = .78$). The addition of group was significant and explained an additional 4% variance ($\Delta R^2 = 0.04$, $p = .001$).

In terms of *reading*, FSIQ was found as a predictor in this analysis, exhibiting a unstandardised B coefficient of 0.04 ($p = .001$). This suggested that for each one-point

increase in FSIQ, the reading score increased by 0.04 units. The standardised coefficient (β) was 0.43, which indicated a moderate to strong effect size suggesting that FSIQ is an important factor in determining *reading* ability. This suggested that higher intelligence, as measured by FSIQ, was associated with better *reading* performance. Furthermore, group was another predictor, presenting a positive unstandardised coefficient *B* of 1.42 (p = .006), which indicated that non-autistic children had a better reading ability than autistic children. The effect size of agecategory was moderate (β = 0.38).

Although the BeeryKin variables were not significant, the submodel explained slightly more variance (0.2%) in *reading* scores compared to the submodel with VMI. This suggested that while the BeeryKin variables were not independent predictors, they potentially provide a better explanation for *reading* than VMI. This indicated that the BeeryKin measures captured some relevant aspects of *reading* performance.

Table 11a. Summary of predictors for the reading DV using hierarchical regression.

Reading	Model 1				Model 2				Model 3				Model 4				Model 5			
	B (SE)	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*
Autism Severity	* **-.32 (.13)**	-.33	-2.47	-.58, -.06	-.02 (.10)	-.02	-.15	-.22, .18	-.05 (.10)	-.05	-.50	-.25, .15	.03 (.13)	.03	.22	-.24, .29	.03 (.13)	.03	.21	-.24, .30
FSIQ					*** **.09 (.01)**	.76	7.39	.07, .11	*** **.07 (.01)**	.60	5.43	.05, .10	*** .07 (.01)	.58	5.07	.04, .10	*** **.07 (.02)**	.56	4.18	.04, .10
Age									-.82 (.49)	-.22	-1.38	-2.01, .38	-.95 (.61)	-.26	-1.55	-2.18, .28	-.96 (.62)	-.26	-1.54	-2.22, .30
Hand-writing fluency									.04 (.02)	.27	1.96	-.001, .08	.03 (.02)	.24	1.072	-.01, .07	.03 (.02)	.24	1.60	-.01, .07
[a]Age_Cat * HF									-.04 (.36)	-.02	-.10	-.76, .69	.03 (.37)	.02	.09	-.71, .78	.04 (.38)	.02	.10	-.72, .79
GEC													-.02 (.02)	-.13	-.89	-.07, .03	-.02 (.02)	-.13	-.87	-.07, .03
VMI																	.02 (.13)	.02	.16	-.25, .29
R	.33				.76				.81				.81				.81			
R²	.11				.58				.65				.66				.66			
Adjusted R²	.09				.57				.62				.61				.61			
SE	1.79				1.23				1.16				1.16				1.17			
Δ R²	.11				.47				.07				.01				.0002			
F	6.11				33.73				17.04				14.27				11.96			

ΔF	6.11	54.66	3.05	.79	.03
df1	1	1	3	1	1
df2	49	48	45	44	43

*p<.05, **p<.01, ***p<.001 a. age-category * handwriting fluency interaction term

Handwriting Fluency

A summary of the hierarchical regression analyses with seven models predicting *handwriting fluency* is illustrated in Table 11b. Model 1, which included age-category was not significant (F (1,59) = 1.14, p =.29, R^2 = .02). Model 2, which included *reading* was significant (F (1, 58) = 21.87*, p < .001,* R^2 = .43*).* The addition of *reading* was significant and explained an additional 41% variance (ΔR^2 = 0.41, p < .001). Model 3, which included VMI was significant (F (1, 57) = 16.26*, p < .001,* R^2 = .46). The addition of VMI was not significant and explained an additional 3% variance (ΔR^2 = 0.03, p = .08). Model 4, which included BeeryKin variables was significant (F (2, 55) = 10.44*, p < .001,* R^2 = .49). The addition of BeeryKin variables was not significant and explained an additional 3% variance (ΔR^2 = 0.03, p = .26). Model 5, which included FSIQ was significant (F (1, 54) = 8.63*, p < .001,* R^2 = .49). The addition of FSIQ was not significant and explained an additional 0.3% variance (ΔR^2 = 0.003, p = .59). Model 6, which included GEC was significant (F (1, 53) = 7.34*, p < .001,* R^2 = .49). The addition of GEC was not significant and explained an additional 0.3% variance (ΔR^2 = 0.003, p = .61). Model 7, which considered all variables was significant (including group) was significant (F (1, 52) = 6.64, p < .001, R^2 = .51). The addition of group was not significant and explained an additional 1% variance (ΔR^2 = 0.01, p = .25).

In terms of *handwriting fluency*, age-category was found as the only predictor exhibiting a unstandardised coefficient B of 9.44 (p < .001) and indicate a low to moderate effect size (β = 0.30). This indicated that older children had better *handwriting fluency* than younger children.

Despite not being statistically significant as standalone predictors, the submodel incorporating BeeryKin variables accounted for a larger variance in

handwriting fluency compared to submodels that included FSIQ or GEC. This suggested that BeeryKin variables, although not significant, provided a more robust explanation of *handwriting fluency* than FSIQ or GEC. Additionally, the variance accounted for by the submodel including VMI was comparable to that explained by the BeeryKin variables, with both showing an increase in R-squared (ΔR^2) of 3%. These results indicate that while BeeryKin variables were not independently significant, they might still be valuable in understanding the factors influencing *handwriting fluency*.

Table 11b. Summary of predictors for *handwriting fluency* (HF) in children.

Hand-writing fluency	Model 1				Model 2				Model 3				Model 4				Model 5			
	B (SE)	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*
Age-Cat	5.35 (3.68)	.20	1.45	-2.05, 12.76	** **10.44 (3.45)**	.39	3.03	3.51, 17.37	* **8.94 (3.43)**	.33	2.61	2.03, 15.85	* **8.65 (3.52)**	.32	2.46	1.67, 15.72	* **8.56 (3.61)**	.32	2.37	1.28, 15.83
Autism Severity	-1.74 (.96)	-.25	-1.81	-3.67, .19	-.24 (.92)	-.03	-.26	-2.08, 1.61	-.10 (.89)	-.01	-.11	-1.90, 1.70	-.22 (.94)	-.03	-.24	-2.11, 1.67	-.10 (1.26)	-.02	-.08	-2.64, 2.43
Reading					*** **3.91 (.97)**	.54	4.03	1.96, 5.86	* **2.81 (1.10)**	.39	2.56	.60, 5.02	* **3.17 (1.34)**	.44	2.37	.48, 5.87	* **3.14 (1.37)**	.44	2.30	.39, 5.90
VMI									2.11 (1.08)	.27	1.96	-.06, 4.28	2.36 (1.20)	.31	1.96	-.06, 4.79	2.35 (1.22)	.31	1.93	-.11, 4.81
FSIQ													-.09 (.18)	-.10	-.49	-.44, .27	-.09 (.18)	-.10	-.49	-.45, .27
GEC																	-.03 (.21)	-.03	-.14	-.46, .40
R	.35				.59				.63				.63				.63			
R²	.12				.35				.40				.40				.40			
Adjusted R²	.08				.30				.34				.33				.32			
SE	12.91				11.24				10.92				11.01				11.13			
∆ R²	.12				.23				.05				.003				.0003			
F	3.28				8.29				7.56				5.99				4.89			
∆F	3.28				16.24				3.84				.24				.02			
df1	2				1				1				1				1			

df2	48	47	46	45	44

*p<.05 **p<.01 ***p<.001

Discussion

The present study investigated two research aims: 1) to examine visuomotor differences between autistic and non-autistic children aged 7 to 11 years old using movement outcomes and production measures (e.g., MT, SPE and kinematic analysis); and 2) to examine the extent to which BeeryKin variables, along with demographic (i.e., age category), cognitive (i.e., FSIQ and executive function), and VMI variables predicted literacy skills (i.e., reading and handwriting skills).

It is important to first note that the findings from 11 out of the 12 VMI performance and planning dependent variables revealed significant task differences between copying and tracing. Specifically, children exhibited shorter movement times, less movement time variability, higher peak velocities, and a shorter percentage time to peak velocities when copying compared to tracing task. These task differences indicated that sensorimotor processes operate differently when performing these tasks, which is consistent with the suggestion (Carlson et al., 2013) that copying and tracing activities in schools are important methods as they engage the sensorimotor system, and associated attentional and cognitive processes, differently during movement preparation and execution.

Significant differences were found in both the VMI Performance (MTsd; SPE; SPEsd) and Planning (%TTPVx1; %TTPVy1; %TTPVy1sd) markers suggesting that autistic children engaged the underlying motor processes differently to the non-autistic children when performing the two tasks. In terms of motor performance, although the autistic children exhibited greater variability in the symbol error production, which is

consistent with many studies (see Gowen & Hamilton, 2013 for a review; and Marko et al., 2015), they were more accurate than the non-autistic group (i.e., a lower SPE score). These findings confirmed the autistic children engaged appropriately with the task instructions and perhaps prioritised accuracy over consistency. The 3-way interaction found movement time variability (MTsd) indicated that the autistic group executed the copying and tracing of triangles differently to the non-autistic group. They performed with less variability when copying triangles compared to tracing triangles, which suggests that when there is a greater requirement to integrate the two visual-motor processing streams during tracing compared to copying motor performance was compromised in autism. This visual-motor integration difference is consistent with the suggestion that autistic children have operational differences in the mechanisms (Gidley Larson et al., 2008) that underpin integration, which is known to impact other associated areas like motor imitation and social interaction (see Ament et al., 2015; Gidley Larson & Mostofsky, 2008; Mostofsky et al., 2007, 2009).

The 3-way interaction also offered an interesting finding in terms of how autistic children approached the process of copying a line versus copying a cross. The difference between the two symbols is that the line requires the motor planning of one segment, whereas the cross requires the motor planning of two segments. In this context, autistic children executed the copying movements with a significantly greater movement time variability in the cross condition. It therefore seems that when autistic children encode and execute a movement that has 2 segments the resulting movement execution is impacted. This processing difference is consistent with other data (Fabbri-Destro et al., 2009) that has shown planning differences in contexts where autistic children are required to plan two movements in advance. In these contexts, autistic

children are suggested to plan the two segments separately, thus not affording the motor system to benefit from the online processes that are operating when performing the first movement in a two-segment task.

In addition to the potential planning differences seen in movement time, the data showed that peak velocity occurred later in movement (%TTPV), and was more variable, in autistic children than non-autistic children. Specifically, it seems that autistic children planned tracing movements differently than non-autistic children such that peak velocity occurred later in movement. A later time to peak velocity (see Elliott et al., 2001; Elliott et al., 2010; Elliott et al., 2020) is indicative of a movement that requires more time to integrate sensorimotor information across the initial stages of movement, resulting in less time to process online visual motor information when tracing the movement trajectory. The effects are consistent with the suggestion that autistic children require additional time to process and integrate visual information for limb-target control (Glazebrook et al. 2009; see also Rinehart et al., 2006a), which could in part could be explained by a less effective planning mechanism that is engaged to process prior information for anticipating upcoming goal-directed actions (Ganglmayer et al., 2019).

The significant differences in sensorimotor control for autistic children supported the rationale for the follow-up hierarchical regression that examined whether VMI predicted *reading* and *handwriting fluency* in children aged 7 to 11 years old. First, and in terms of the required correlation analyses needed for regression, the motor variables SPE and %TTPV were significantly correlated with *reading*, whereas only %TTPV was correlated with *handwriting fluency*. These significant findings are consistent with

previous research suggesting that motor VMI, particularly in tasks involving symbol production, influence reading abilities (Cameron et al., 2012; 2016; Carlson et al., 2013). Specifically, the correlation between the visuomotor planning marker (%TTPV) and *reading* suggested a relationship between motor planning and literacy skills. The correlation between SPE, which reflects the accuracy of symbol production, and *reading* underscored the importance of motor control in literacy development (Waterman et al., 2014). Similarly, the association between %TTPV, a measure of motor planning, and reading highlighted the role of visuomotor integration in processing written language. Only %TTPV was correlated with *handwriting fluency*, indicating a specific association between motor planning and the ability to produce written text fluently. This finding suggested that the temporal aspect of motor planning, as captured by %TTPV, played a role in handwriting performance.

In terms of the regression findings, similar in Chapter 4, the main predictor for *reading* was general intelligence, as reflected by FSIQ scores, and not VMI. This finding is consistent with research showing a crucial role of FSIQ in reading proficiency (Christopher et al., 2012; Cutting & Scarborough, 2006; Mayes et al., 2007). The current findings indicated that VMI was not a predictor for reading for children in Key Stage 2. This underscored the importance of general cognitive abilities, in facilitating word recognition and comprehension skills for all children, highlighting that intellectual functioning facilitated greater reading achievement.

Moreover, these regression findings corroborated with the results obtained in Chapter 4. Notably, FSIQ scores, emerged as a significant predictor for *reading* (i.e., word reading and reading comprehension). This reaffirms the pivotal role of cognitive

abilities in literacy acquisition, suggesting that higher levels of intellectual functioning contribute to enhanced comprehension skills (MacKinnon, 2008; Preacher & Kelley, 2011).

The only predictor for *handwriting fluency* was age-category, which indicated that older children demonstrated greater proficiency in motor tasks associated with literacy such as handwriting. This age effect replicated previous work that also examined the predictors of handwriting in autistic and non-autistic children aged 7-12 years of age (Hellinckx et al., 2013), which showed that age was the strongest predictor, alongside gender, VMI and executive function (Rosenblum et al., 2009). The fact that the other variables such as VMI, FSIQ, GEC, and reading are not predictors in the current Chapter suggests that over the course of age-development children had acquired some tasks specific experience that led to age being the predictor. The current data and regression analysis does not offer an insight in what underpins the specific experience, but it is likely that across development children would have learned to develop handwriting quality and speed (Graham et al., 1998; Rueckriegel et al., 2008; Ziviani & Elkins, 1984), leading to the refinement of the essential writing components as a function of increased formal handwriting instructions and practice (see Beery et al., 2004; Marr et al., 2003; Marr & Dimeo, 2006). Although it is not surprising that handwriting fluency improves with age, it is notable that age was the only significant predictor in this analysis. This may also be influenced by the fact that the handwriting fluency measure was not controlled for age, unlike other measures in the study.

BeeryKin Variables as Independent Variables to Predict Literacy Outcomes

Furthermore, the inclusion of BeeryKin variables, which assessed VMI planning and performance, contributed to a more comprehensive understanding of the motor aspects of literacy development. Based on the literature, this study represented one of the first attempts to utilise motor control variables in examining predictors of literacy outcomes in children aged 7 to 11 years old. The BeeryKin variables, specifically SPE (symbol production error) and %TTPV (percentage time to peak velocity), did not emerge as significant predictors in the regression analysis for *reading* skills. There could be several reasons for this lack of predictive power. Firstly, the BeeryKin variables may not capture the specific cognitive or motor processes crucial for reading skills as effectively as other measures, such as FSIQ. While SPE reflects the accuracy of symbol production and %TTPV indicates motor planning efficiency, these measures may not directly tap into the cognitive processes underlying reading comprehension and word recognition. Although these variables did not independently predict literacy outcomes, the collective contribution suggested that motor skills, as assessed by BeeryKin, may have some influence in *reading* and *handwriting fluency* as there were significant linear relationships between BeeryKin variables and literacy skills. This highlighted the importance of considering motor proficiency alongside cognitive abilities in literacy interventions, particularly for autistic children who may have experienced VMI challenges.

Limitations

This study has offered valuable insights into the predictors of literacy skills in children, yet it is crucial to acknowledge several limitations. Firstly, the relatively modest sample size restricts the generalisability of the findings, as a larger and more diverse

sample could have facilitated a more robust examination of the intricate interplay between cognitive, motor, and demographic factors in literacy development. Additionally, while hierarchical regression analysis was informative, it may not have fully captured the complexity of these relationships. Future investigations employing advanced statistical techniques such as structural equation modelling could offer a more nuanced understanding of the underlying mechanisms driving literacy outcomes.

Another limitation pertains to the exclusive focus on symbols as stimuli for visuomotor tasks. While symbols are commonly employed in assessing visuomotor skills, they may not comprehensively represent the array of writing tasks encountered in real-world literacy contexts. Incorporating a broader range of stimuli, including letters, words, or sentences, could have provided a more holistic understanding of the motor mechanisms underlying literacy skills. Furthermore, the study did not explore potential interactions between cognitive and motor factors in predicting literacy outcomes, which could have yielded valuable insights into the developmental trajectories of literacy skills in children. To enhance the comprehensiveness of future investigations, it may be valuable to incorporate a broader range of literacy variables such as spelling and oral language, thus capturing a larger spectrum of literacy skills in children aged 7 to 11 years old. By addressing these methodological limitations, forthcoming research can build upon the current findings, refining interventions and expanding understanding to effectively facilitate the literacy development of autistic children aged 7 to 11 years old.

Implications

The implications of this study extend to the development of motor-focused interventions within literacy programs for children aged 7 to 11 years old (Houwen et

al., 2016; Santi, 2015). By recognising the interplay between cognitive, VMI and underlying motor mechanisms factors in shaping literacy outcomes, educators and clinicians can design interventions that specifically target motor skills alongside cognitive abilities.

Moreover, early identification and intervention are crucial in addressing motor related challenges in literacy acquisition, particularly among autistic children. Previous literature that investigated early-age and kindergarten children emphasised the importance of VMI in associated school readiness skills. (Cameron et al., 2012, 2015 & 2016; Pagani & Messier, 2012). Integrating motor components into intervention strategies from an early age allows for targeted support tailored to the unique motor needs of each child. By providing early interventions that address motor coordination and planning difficulties, educators and clinicians can mitigate potential barriers to literacy success and promote optimal motor and literacy development.

Conclusion

In summary, this research sheds light on the factors influencing literacy proficiency in children aged 7 to 11, emphasising the key role of FSIQ and age, but other associated visual-motor integration processes. By incorporating the BeeryKin variables, this study offers a novel approach to understanding the motor aspects of literacy development, which may be more apparent with future examination of the mediation between FSIQ and VMI. These findings underscore the importance of tailored literacy interventions that consider individual cognitive and motor differences, particularly in children with neurodevelopmental disorders like autism. Adopting a

holistic approach to intervention can enhance reading and handwriting fluency, equipping children with essential skills for literacy success.

Chapter 6: Teachers' Beliefs, Knowledge and Frequency of Activities of Motor Skills in 7- to 11-year-old Autistic Children in the United Kingdom

Introduction

Motor skills, encompassing both fine and gross motor abilities, play a crucial role in children's physical development and school readiness, with research indicating that these skills can predict social skill differences in autistic children (Happe et al., 2017; Teitelbaum et al., 1998). Based on the findings of systematic review and experimental studies, they highlighted sensorimotor differences in autistic children in Key Stage 2, such as slower movement and variability (Teitelbaum et al., 1998). Given the significant effect of motor skills on key outcomes in autism [e.g., adaptive daily living skills (Travers et al., 2017), language ability (Bedford et al., 2016); social communicative skills (MacDonald et al., 2013)], physical education (PE) has been recommended to teachers in the UK national curriculum for primary and secondary school as an important subject for special needs children, as it will help them reach key movement. This survey study aims to further investigate teachers' perspectives on motor skills and their integration into physical education, addressing a critical gap identified in my earlier research on skill milestones for children, such as writing and the ability to catch and throw a ball (Morley et al., 2021).

Schools (e.g., SEN support, autism specialist, school curriculum) may serve as a crucial environment for children's motor skills development because children spend an average of 5-8 hours in school with teachers (Van Rossum et al., 2019). Motor skills developed in school have been shown to positively impact children's academic outcomes (e.g., literacy) and daily living skills (e.g., decoding letters and

words, solving quantitative problems, and interacting effectively with peers and adults) (Becker et al., 2014; Grissmer et al., 2010). However, the lack of teachers specialising in physical education in UK primary schools (Ofsted, 2013) means that the responsibility of providing motor skills intervention is placed on any number of teachers, including head teachers and teaching assistants. Maher & Fitzgerald (2020) raised concerns about the lack of staff trained in providing motor skills development in PE lessons. It remains to be investigated to what extent teachers have sufficient skills to work with autistic children and adolescents on motor skills in SEN and mainstream schools.

Despite the fact that motor skills development is key for autistic children's social development (Chen et al., 2022) and there is a lack of teacher training in autistic children's motor skills development (Maher & Fitzgerald, 2020), no current research has documented teachers' education on motor skills in autistic children aged 7-11 years in schools (mainstream or SEN schools). Ernest (1989) suggested that school education was influenced by teachers' beliefs and knowledge of the subject, such as literacy and maths skills. Previous studies have suggested that for teachers to successfully implement a classroom practice, their beliefs in the practice are crucial (Landers et al., 2003; Rogers, 2003). While past surveys have been used to assess other variables in teachers, few studies have focused on teachers' beliefs, knowledge, and the frequency of activities in motor skills. Costa et al. (2021) investigated early years practitioners' training, beliefs and practices concerning maths to inform the implementation of education and practice of maths.

Teachers' Beliefs of Motor skills

Teachers' individual beliefs about appropriate teaching content and activities (Brown, 2005) are closely linked to classroom performance. Motor skills are usually assessed during school Physical Education (PE) lessons (Ericsson & Karlsson, 2014). Harris et al. (2012) suggested that PE lessons in primary school were usually delivered by a generalist teacher, with 6 hours of training, rather than PE specialists, with a minimum of 1 year of training. Based on the Department of Education's 2015 report on primary school PE classes, more than half of all classes (54%) are taught by a generalist teacher with limited knowledge and skills and a lack f confidence in teaching children in a PE lesson (Harris et al., 2012; Morgan & Bourke, 2008). Therefore, it is essential to gain further insights into teachers' understanding of motor skills and PE classes in SEND and mainstream schools to better serve autistic children's motor skills development during a critical stage of development.

Teachers' Knowledge of Motor Skills

Teachers' knowledge of autistic children's motor skills may influence their beliefs about motor skills and other academic skills, such as maths, as well as their classroom practice (Coleman & Dyment, 2013). Motor skills, especially fine motor skills, are involved in tasks such as writing numbers, drawing shapes, and manipulating objects for counting, which are fundamental in early math learning (Fischer et al., 2020). If teachers have more knowledge of motor skills, they may associate challenges in motor tasks with potential difficulties in math-related tasks, even though these domains are not directly linked. According to Callea et al. (2008), most of the teachers in school feel ill-equipped to teach PE because they do not have sufficient knowledge of motor skills and/or physical exercise. Teachers' knowledge of fundamental movement skills

(e.g., locomotion, balance, manipulative skills) is an influential factor in students' motor skill acquisition (Newell, 2020). It is of concern that generalist class teachers receive limited training on motor skills and physical exercise (Harris et al., 2012; McLachlan et al., 2013), due to lack of information, knowledge, skills (Kolt et al., 2005) and a lack of confidence (Oliver et al., 2007) on teaching motor skills.

The Frequency with which Teachers Engage their Students in Motor Skill Activities

Teachers' classroom practice may also be influenced by their beliefs and knowledge of the subject. When teachers place more importance on a subject, such as maths, they tend to execute subject-related activities in the classroom with more frequency and creativity (Brickhouse, 1990; Cheung, 2012). According to Brickhouse (1990), teachers' view of certain subjects might be expressed in their classroom instruction and enhanced by their frequency of classroom practice and further knowledge of the subject. Cheung (2012) also found that teachers' beliefs would influence the creativity, instruction, and frequency of the classroom practice. These findings suggest that teachers' classroom practice of certain subjects may also influence other areas and aspects of teaching, such as their prior knowledge, whether they had trained on the subject and feedback from students. In the current literature, few papers have focused on classroom practice on motor skills in teachers, and classroom practice was important to examine along with teachers' beliefs and knowledge in motor skills.

Although there is an increasing focus on motor skills in SEN schools (Morley et al., 2021; Van Rossum et al., 2018), to the author's knowledge there are no studies specifically focused on teachers' beliefs, knowledge and frequency of activities

involving motor skills of autistic children and adolescents in both mainstream and SEN schools. Why might this be? It could be that motor skills are not the primary skills (e.g., academic skills) required in the school setting. In the UK national curriculum, the importance of motor skills in relation to other essential skills (e.g., social skills, academic skills and daily living skills) for child development are not mentioned, and there is limited information on motor skills activities for each key stage. Although teachers often report higher confidence in teaching language-related skills, e.g., literacy (Copley, 2004) and life skills (Shechtman et al., 2005), because they have received more training on life and literacy skills (Shechtman et al., 2005), their confidence in motor skills is lacking (Callea et al., 2008) because they have received limited training on motor skills and PE (Harris et al., 2012). Thus, it is essential to develop a new tool to measure teachers' beliefs, knowledge and frequency of activities involving the motor skills of autistic children in SEN and mainstream schools.

Current Study

This study aims to understand SEN and mainstream teachers' beliefs on the importance of learning about motor skills, the knowledge of motor skills, and the frequency of motor skill activities in autistic children aged 7-11 years compared to other skills taught in school (i.e., literacy and maths). The research questions are fourfold:

1 What are teachers' beliefs about the importance of autistic children aged 7-11 years learning motor skills, compared to literacy and maths skills? It is hypothesised that teachers believe literacy and maths skills are more important than motor skills to autistic children aged 7-11 years.
2 What do teachers know about motor skills performed by autistic children aged 7-11 years, compared to literacy and maths skills? It is hypothesised that teachers will

have more knowledge of literacy and maths skills than motor skills for autistic children aged 7-11 years.

3 How frequently do teachers offer motor skills activities to autistic children aged 711 years, compared to literacy and maths skills? It is hypothesised that teachers would report offering more literacy and maths activities than motor skills-related activities to autistic children aged 7-11 years.

4 What are the predictors for teachers' beliefs, knowledge and frequency of activities of motor skills? It is hypothesised that school type can be a predictor that SEN school teachers place more importance on motor skills, have more knowledge of motor skills, and more frequent motor skills-related activities compared to mainstream teachers.

Methods

Participants

The survey was viewed by 266 potential responders, but 70 responders did not complete any survey items (including consent forms), and 46 responders just completed the consent form. The remaining data were examined, and the answers of those who only answered demographic information (*n* = 24), only answered demographic and belief section survey items (*n* = 6), and only answered demographic, belief and knowledge section survey items (*n* = 6) were excluded from the analysis. In the final dataset, teachers' responses were included and varied based on different sections for analyses: belief (*n* = 126); knowledge (*n* = 120); frequency of activities (*n*=114).

A total of 126 volunteer teaching staff (e.g., head teachers, teaching assistants and SENCOs) took part in the survey (see Table 12). This survey included teaching staff to provide a broader and more comprehensive understanding of the belief, knowledge and frequency of activities of different roles within the school system, as most of them have the opportunity to engage with autistic children on motor skills development. Most respondents were female (75%). More than half of the teachers were young adults (aged 18-29; 52%). Half of the included teachers were from SEN schools (47%) working as class teachers (30%) or teaching assistants (29%). More than half of them had less than 4 years of teaching experience working with autistic children (60%).

Over a third (38%) of the teachers (*n* = 43) had received special education needs training (e.g., AET, SCERTS and TEACCH) (see Table 12.1) while 22% of teachers reported having received motor skills and/or physical development training (e.g., OT training, TEFL and Twilight), 39% of teachers reported that they had received literacy training (e.g., phonics, writing and reading training) and 33% of them reported that they had received maths training (e.g., Singapore maths, numeracy and informal maths training). Specifically, for motor skills related training, some teachers put TEFL (Teaching English as a Foreign Language) as an answer that could either be a mistake, or they might find a connection between language instruction and motor skills, as activities like handwriting and using physical tools can involve fine motor tasks essential for language learning. In terms of Twilight, according to the *SEND & Inclusion Autumn 2024 training brochure*, it is a brief, after-school professional development session designed to enhance the skills of primary school teachers and teaching

assistants in supporting autistic children and young people, particularly in motor skills development and other learning needs.

Table 12. Illustration of teaching staff's demographic information

Demographic Information	N	%
Gender		
Male	26	22.8
Female	86	75.4
Non-binary / third gender	1	0.9
Prefer not to say	1	0.9
Age group		
18-29	59	51.8
30-39	29	25.4
40-49	17	14.9
50-59	7	6.1
60+	2	1.8
Highest level of education		
Level 6 and above	93	81.6
Level 5	11	9.6
Level 4	2	1.8
Level 3	6	5.3
Level 2 and below	1	0.9
No qualifications	1	0.9
Ethnicity		
White	73	64.0
Irish	5	4.4
Gypsy or Irish Traveller	1	0.9
Asian or Asian British	18	15.8
Black, African, Caribbean, or Black British	8	7.0
Mixed or multiple ethnic groups	4	3.5
Other	5	5.4
Living area		
England	74	64.9
Wales	4	3.5
Scotland	5	4.4
Northern Ireland	1	0.9
Other	30	26.3
School type		
Mainstream school	60	52.6
Special Education Needs school	54	47.4
Job role		
Class teacher	34	29.8
Teaching assistant	33	28.9
Headteacher	2	1.8

Special educational needs coordinator (SENCO)	2	1.8
Senior leader	9	7.9
Middle leader	8	7.0
Other	26	22.8
Teaching experience		
Less than 1 year	34	29.8
1-4 years	33	28.9
5-9 years	22	19.3
10-14 years	12	10.5
14+ years	13	11.4

Table 12.1 Illustration of teachers' types of training and duration

Special Needs Education Training	N	%	Type of Training (Top 3)	N	Duration
Yes	43	37.7	AET	12	1 day
			SCERTS	7	1-3 days
			TEACCH	4	1-2 days
No	71	62.3			

Motor Skills Related Training	N	%	Type of Training (Top 3)	N	Duration
Yes	25	21.9	OT training	13	1 hour – 3 days
			TEFL	1	120 hours
			Twilight	1	3 hours
No	89	78.1			

Literacy Skills Related Training	N	%	Type of Training (Top 3)	N	Duration
Yes	44	38.6	Phonics	22	3 hours – 3 days
			Writing	8	1 hour – 3 weeks
			Reading	6	1 hour – 3 months
No	70	61.4			

Maths Skills Related Training	N	%	Type of Training (Top 3)	N	Duration
Yes	37	32.5	Singapore Maths	11	2 hours – 3 days
			Numeracy	3	1 – 3 months
			Informal Maths	6	0.5 hour – 1 week
No	77	67.5			

Procedure

Participants were recruited through convenience sampling of supervisors' (S.J.H. & K.W.) professional networks of various UK school settings and professional societies. Participants received an email containing a brief description and Qualtrics link of the study through headteachers, class teachers and research leads from partner schools, social media platforms (e.g., Twitter, Facebook) and word of mouth. Teachers gave consent and completed a 20-minute online English survey where survey blocks were randomly presented to each participant to minimise order effects. Ethics was received and approved by IOE, Institute of Education and Society, University College London, with data protection No. Z6364106 on 18th March 2022.

Materials

We conducted a newly developed online teacher-reported survey on teachers' understanding of motor skills in autistic children aged 7 to 11 years. Survey items were drawn from Costa et al.'s (2021) preschool practitioners' training, beliefs and practices concerning mathematics, and modified to assess teachers' beliefs, knowledge, and frequency of motor skills activities for autistic children. Survey items were designed by P.Y. and S.J.H. with the help of K.W. and distributed to teachers with experience

working with autistic children aged from 7 to 11 years in SEN and mainstream schools. This survey contained 72 closed-ended questions (average time to complete = 15 minutes) on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) measuring teachers' beliefs, knowledge, and activities of motor skills in autistic children aged 7-11 years (Key Stage 2) and other school skills (e.g., literacy and maths skills) launched on Qualtrics between 27th March and 26th September 2022. (https://uclioe.eu.qualtrics.com/jfe/form/SV_6VTvXiNZJlyYENU).

The survey questions were designed based on the Autism Education Trust (AET) standards. AET schools' autism standards for all schools and educational settings for autistic students aged between 5 and 16 years old were used to guide the learning and development aspects in the survey (DfA, 2017). These standards guided the learning and development aspects of the survey, focusing on the needs of the students that the survey participants had taught. The AET standards included learning outcome goals across persona, social and emotional development (e.g., building relationships and communication) and specific subject domains adapted by the Ofsted handbook of school inspection (e.g., literacy, physical activities). Based on the handbook, in terms of literacy, autistic students in general were required to have skills in reading, writing and oral communication that access different areas of the curriculum (e.g., reading and discussing what was read). In terms of physical activities, autistic students in general were required to achieve complex sequential movements (e.g., kicking and trapping a ball) and the ability to write. The standards also guided the quality of teaching, learning, assessment support, and skills of teachers.

The final survey assessed teachers': 1) *beliefs* towards motor, literacy and maths skills; 2) *knowledge* of motor, literacy and maths skills; 3) *frequency* in which they implemented motor, versus literacy and math activities in the school. Participant demographic information was collected as potential control variables in the analyses (e.g., age, job role and years in teaching).

Teachers' beliefs of motor, literacy, and maths skills

The first 18 items assessed teachers' beliefs on three specific skills in autistic children aged 7 to 11 years old. All participants were required to have experience working with autistic children within this age range. Some of them might have taught one or more age range of autistic students across different age ranges. All 18 items were accurate statements supported by research evidence. These were six items on *beliefs of motor skills* (e.g., 'When learning motor skills like netball, or cricket, autistic children also learn social skills like nonverbal communication such as eye contact and gestures.'), *beliefs of literacy skills* (e.g., 'When learning literacy skills like reading, autistic children also learn processes that could help them learn other maths skills like problem solving.'), and *beliefs of maths skills* (e.g., 'After learning maths skills like counting, autistic children can engage in other maths-related activities while shopping in a supermarket.'). Responses were summed to calculate the mean scores of each domain (i.e., motor skills, literacy skills, and maths skills). In terms of general belief scale (full 18 items), the internal reliability was excellent (α =. 93). In terms of the belief subscales, the internal reliability of belief of motor skills, literacy and maths was good (α =. 82; .79; .83 respectively).

Teachers' Knowledge of Motor, Literacy, and Maths Skills

The second part of the survey, a 30-item self-report questionnaire on a 5-point Likert scale from 1 (strongly disagree) to 5 (strongly agree) assessed teachers' knowledge on three specific skills in autistic children aged 7 to 11 years old. These included: 10 items on the knowledge of motor skills (e.g., 'Autistic children and non-autistic children take a similar amount of time to plan movements, such as putting a pencil into a pencil case. '), knowledge of literac*y skills* (e.g., 'Autistic children are typically expected to use language in various situations in Key Stage 2, such as drama, formal presentations and debate.'), *knowledge of maths skills* (e.g., 'Autistic children are typically expected to read and write numbers up to 1,000 in numerals and in words in Key Stage 2.'). The response from the Likert style was calculated in the mean scores of each domain (i.e., mean score of motor skills, mean score of literacy skills, and mean scores of maths skills). Specifically, half of the knowledge were false and reverse coded when conducting analysis. As illustrated in Table 13, reverse coded items were shown with a 'R' at the end of the statement. In terms of the general knowledge scale (full 30 items), the internal reliability was excellent (α =. 91). In terms of the knowledge subscales, the internal reliability of knowledge of motor skills was poor (α =. 54); the internal reliability of knowledge of literacy and maths skills was good (α =. 89; .90 respectively). For the knowledge of motor skills section, analyses (e.g., exploratory and confirmatory analyses) were further conducted to examine the scale reliability and validity (see results section for more detail).

Differences between Belief and Knowledge Statement: According to Griffin & Ohlsson (2001), belief and knowledge represent different qualitative aspects of mental representations. Belief reflected true value assigned to the proposition, that can

shape perceptions, influence behaviours, and guide decision-making processes (Seitz & Angel, 2020). For instance, a statement like "When learning motor skills in sports, autistic children also learn social skills like nonverbal communication" expresses a belief about the interconnectedness of motor and social skills. Although this belief is supported by research (Meyer et al., 2017), its significance lied in whether teachers considered it to be true. Understanding teachers' beliefs about the link between motor skills and social development in autistic children is important, as these beliefs can shape their teaching methods and how they interact with students. In terms of knowledge, it referred to the representation of a proposition, whereas knowledge statements involve facts that can be empirically verified or supported by research findings (Southerland et al., 2001). In this study, for example, the statement " Compared to non-autistic children, autistic children that have poor motor skills like struggling to write in a straight line are more likely to have poorer social skills that lead to difficulty in understanding informational gestures such as waving and high-fives. " was supported by research findings (Ohara et al., 2019). The primary difference between beliefs and knowledge is that beliefs are subjective and often represent personal opinions, while knowledge is based on empirical evidence that can be verified objectively.

Teachers' Frequency of Activities to Develop Motor, Literacy and Maths Skills

The third part of the survey, a 24-item self-report questionnaire on a 7-point Likert from 1 (not at all) to 6 (several times a day), with the option of 0 (not age appropriate) assessed teachers' knowledge on three specific skills in autistic children aged 7 to 11 years old. These included: eight items on the *frequency of activities of motor skills* (e.g., 'Autistic children do indoor exercises alone, such as Kids' Yoga'.),

eight items were on the *frequency of activities of literacy skills* (e.g., 'Autistic children read words out loud from a story book/poem.'), and eight items were on the *frequency of activities of maths skills* (e.g., 'Autistic children solve maths problems from a maths workbook.'). The response of "not age appropriate" was not included in the mean score calculation. The response from the Likert scale was calculated in the mean scores of each domain (i.e., mean score of motor skills, mean score of literacy skills, and mean score of maths skills). In terms of general frequency of activities scale (full 24 items), the internal reliability was good (α =. 88). In terms of frequency of activities subscales, the internal reliability of frequency of activities of motor skills, literacy and maths was good (α = .84; .86; .84 respectively).

Data Analysis

Teachers reported on age, gender, level of education, ethnicity, living area, school type, job role, teaching experience, types and frequency of training they have received on SEN, motor, literacy, and maths skills. Kurtosis and skewness of each scale (e.g., beliefs of motor, literacy and maths skills) were conducted to see whether all variables were normally distributed (see Table 13). The cut-off value for kurtosis was between -7 and +7, and for skewness was between -2 and +2 (Bryne, 2010; Hair et al., 2010).

ANOVA Analyses for Mean Differences

A one-way between-subject ANOVA was used to examine the mean difference of each section (i.e., beliefs, knowledge and activities) on domains (i.e., motor skills, literacy skills and maths skills). Post-hoc least significant difference (Bonferroni) test

was used to examine the pairwise comparisons between the domains (i.e., motor skills vs literacy skills; motor skills vs maths skills; literacy skills vs maths skills) of each section.

Table 13. Descriptive Statistics for Survey Items on Teachers' Beliefs, Knowledge and Frequency of Activities of Motor Skills

Item	Mean	SD	Skewness	Kurtosis
Beliefs				
When learning motor skills in sports, like netball or cricket, autistic children also learn social skills like nonverbal communication such as eye contact and gestures.	3.97	0.86	-1.32	2.71
When learning motor skills like moving cubes in time and space during a grouping task, autistic children also learn maths skills like discriminating between symbols (e.g., numbers and arithmetic signs).	4.01	0.68	-0.68	2.26
When learning motor skills like handwriting, autistic children also learn literacy skills like reading and speaking.	3.74	0.87	-0.76	0.37
After learning motor skills like catching a ball with two hands, autistic children can engage in physical activities like playing frisbee in the park.	3.85	0.81	-0.35	-0.24
When learning motor skills like dancing or hopscotch, autistic children also improve mental health and wellness.	4.04	0.72	-0.49	0.35
When learning motor skills like performing clapping games, autistic children also learn skills like play and daily living skills, such as using a knife and fork.	3.60	1.02	-0.50	-0.32
When learning literacy skills like listening and speaking, autistic children also learn social skills like nonverbal communication, such as eye contact and gestures.	3.95	0.92	-0.93	0.58
When learning literacy skills like reading, autistic children also learn processes that could help them learn other maths skills like problem solving.	3.80	0.75	-0.69	0.57
When learning literacy skills like writing, autistic children also learn movements that could help them with other motor skills like playing table tennis.	3.55	1.04	-0.60	-0.08

After learning literacy skills, autistic children can engage in more literacy-related activities such as sound games.	3.40	0.85	1.15	0.36
When learning literacy skills like discussing their ideas of a book, autistic children also improve their mental health and wellness.	3.82	0.83	-0.41	-0.27
When learning literacy skills like speaking, autistic children also learn other skills like language and communication.	4.16	0.72	-0.71	0.67
When learning maths skills like counting with cubes, autistic children also learn social skills like nonverbal communication, such as eye contact and gestures.	3.55	1.03	-0.54	-0.24
When learning maths skills like understanding shapes and arithmetic signs, autistic children also learn literacy skills like reading.	3.68	0.93	-0.85	0.60
When learning maths skills like finger counting, autistic children also learn motor skills like drawing.	3.55	0.95	-0.50	0.25
After learning maths skills like counting, autistic children can engage in other mathsrelated activities while shopping in a supermarket.	2.88	1.21	0.94	-0.63
When learning maths skills like mental maths, addition and subtraction games, autistic children also improve their mental health and wellness.	3.40	0.94	-0.11	-0.65
When learning maths skills like comparing objects (e.g., “point to the tallest and shortest plants”), autistic children also learn language and daily living skills like recognising words and signs in daily life.	3.93	0.86	-0.72	0.54
Knowledge				
Autistic children and non-autistic children walk at a similar speed. (R)	2.76	1.09	0.20	-0.78

Compared to non-autistic children, autistic children that have poor motor skills like struggling to write in a straight line are more likely to have poorer social skills that lead to difficulty in understanding informational gestures such as waving and high-fives.	3.38	1.02	-0.30	-0.67

Compared to non-autistic children, autistic children usually have similar muscle strength (R)	3.01	1.12	0.13	0.87
Autistic children and non-autistic children take a similar amount of time to plan movements, such as putting a pencil into a pencil case (R)	2.59	0.99	0.41	-0.75
Autistic children and non-autistic children have similar strength when gripping an object, such as drawing with crayons (R)	2.82	0.99	0.21	-0.75
Compared to non-autistic children, autistic children struggle more to plan tasks that contain lots of movements, such as keyboard typing, piano playing or buttoning a blouse.	3.73	0.91	-0.89	0.64
Compared to non-autistic children, autistic children show more variable handwriting, e.g., writing their name outside the lines on paper.	3.54	1.00	-0.56	-0.26
Compared to non-autistic children, autistic children react quicker when playing computer games, such as Minecraft (R)	3.06	0.85	-0.29	0.10
Compared to non-autistic children, autistic children sway more when walking across a balance beam.	3.35	0.79	-0.38	0.41
Autistic children and non-autistic children can learn about handwriting by copying their classmates.	3.29	0.89	-0.30	-0.45
Autistic children are typically expected to use language in various situations in Key Stage 2, such as drama, formal presentations and debate.	3.13	0.96	-0.39	-0.53
Autistic children are typically expected to read a wide range of fictional and non-fictional literature in Key Stage 2, such as stories, novels, essays, reviews and journalism. (R)	3.11	1.03	-0.26	-0.70

Autistic children are typically expected to identify and interpret themes, ideas and information in Key Stage 2, such as an author's opinion about the main character in the book (R).	3.18	0.89	-0.30	-0.81
Autistic children are typically expected to be familiar with simple phrases and language that occur in stories and poetry in Key Stage 2.	3.55	0.85	-0.47	-0.05

Autistic children are typically expected to study grammatical features of texts they read in Key Stage 2 (R)	3.25	0.90	-0.45	-0.80
Autistic children are typically expected to make critical comparisons across texts in Key Stage 2 (R)	2.95	0.87	-0.14	-0.77
Autistic children are typically expected to understand what they read by asking questions to improve their understanding in Key Stage 2.	3.46	0.91	-0.64	-0.25
Autistic children are typically expected to retrieve, record and present information from non-fiction in Key Stage 2, such as essays.	3.07	0.94	-0.21	-0.84
Autistic children are typically expected to draft and write narratives, describing settings, characters and atmosphere, and integrating dialogue to convey character and advance the action in Key Stage 2 (R)	3.04	0.95	-0.20	-1.06
Autistic children are typically expected to join in with the class to talk about what they are reading, taking turns and listening in Key Stage 2.	3.54	0.88	-0.50	-0.24
Autistic children are typically expected to use a calculator and other technologies to calculate results and then to interpret them appropriately in Key Stage 2. (R)	3.01	1.01	-0.18	-0.63
Autistic children are typically expected to calculate arc lengths, angles and areas of sectors of circles in Key Stage 2, i.e., shape learning and correct use of maths formulas to calculate arc lengths. (R)	2.92	0.95	-0.15	-0.50
Autistic children are typically expected to read and write numbers up to 1,000 in numerals and in words in Key Stage 2.	3.23	1.00	-0.31	-0.52

Autistic children are typically expected to solve problems involving percentage change (e.g., percentage increase and decrease) in Key Stage 2. (R)	2.89	0.94	-0.11	-0.74
Autistic children are typically expected to learn about adding and subtracting fractions with the same denominator within one whole in Key Stage 2, such as ⅕ + ⅗= ⅘.	3.03	1.03	-0.25	-0.70
Autistic children are typically expected to learn about using and interpreting algebraic notation in Key Stage 2, including 3y in place of y + y + y and 3 × y. (R)	2.76	1.00	0.06	-0.46

Autistic children are typically expected to learn about comparing lengths (m/cm/mm) in Key Stage 2, such as 2cm > 1cm.	3.41	0.97	-0.61	0.08
Autistic children are typically expected to understand that perimeters can be expressed algebraically as 2 (a + b) in Key Stage 2, such as 2 (3+4) = 2 x (7) = 14.	2.72	0.89	-0.11	-0.41
Autistic children are typically expected to learn about constructing and interpreting tables and charts in Key Stage 2, such as frequency tables, bar charts and pie charts. (R)	3.21	0.92	-0.57	-0.28
Autistic children are typically expected to be able to measure heights and lengths of an object using a ruler in Key Stage 2, such as the length of a screwdriver in maths workbooks.	3.54	0.92	-0.47	-0.11
Frequency of Activities				
Autistic children play alone in the playground, such as jumping on a trampoline, swinging on a swing or riding a scooter.	3.74	1.52	0.29	-0.91
Autistic children play with teaching staff/classmates in the playground, such as chasing, playing hide and seek or playing football.	3.67	1.50	-0.02	-0.75
Autistic children do indoor exercises alone, such as kids' yoga.	3.58	1.53	-0.18	-0.51

Autistic children do indoor exercises with teaching staff/classmates, such as dancing in pairs or in a group.	3.61	1.49	-0.24	-0.52
Autistic children do fine motor skills alone in the playground, such as using chalks to draw on the playground floor.	4.19	1.55	0.08	-0.59
Autistic children do fine motor skills with teaching staff/classmates in the playground, such as planting flowers and vegetables.	3.84	1.39	0.00	-0.59
Autistic children do tabletop activities alone, such as fingerprints, cutting paper and using glue.	4.04	1.50	0.15	-0.54

Autistic children do tabletop activities with teaching staff/classmates, such as baking, chopping vegetables and playing chess.	3.53	1.48	0.16	-0.27
Autistic children play phonics games, such as sound baskets and twister.	4.27	1.61	-0.20	-0.57
Autistic children read picture books using finger pointing to words.	4.10	1.60	0.09	-0.48
Autistic children read words out loud from a storybook/poem.	3.66	1.53	-0.11	-0.53
Autistic children use educational software or apps to learn about phonics, letters and sounds.	3.77	1.60	0.03	-0.53
Autistic children discuss information in fiction books, such as what the characters are doing.	3.60	1.52	-0.10	-0.54
Autistic children make comparisons across different types of books, such as non-fiction and fiction books.	3.68	1.49	-0.47	-0.34
Autistic children refer to letters or written words in the environment, such as identifying letters on road signs.	4.00	1.49	-0.21	-0.59

Autistic children share their opinions about a book, such as why they like a particular poem.	3.74	1.62	-0.16	-0.67
Autistic children use educational software or apps to learn about maths, such as Topmarks, or Number Bombs.	3.67	1.57	0.20	-0.54
Autistic children play mental calculations games, such as Treasure Hunt, or Zap.	3.58	1.54	-0.17	-0.44
Autistic children practise problem solving in maths in a group, such as putting number flashcards in a basket together and adding them up with another classmate.	3.61	1.41	-0.02	-0.12
Autistic children solve maths problems from a maths workbook.	4.19	1.51	0.02	-0.38

Autistic children play board games involving numbers, such as snakes and ladders.	3.84	1.52	0.24	-0.09
Autistic children use Lego bricks or cubes to learn grouping with teaching staff/classmates.	4.04	1.50	0.24	-0.02
Autistic children refer to numbers in the environment to learn maths, such as 2 cakes for each of the 3 people in the bakery.	3.53	1.53	0.03	-0.43
Autistic children learn maths in the playground with teaching staff/classmates, such as counting the shots while playing basketball.	4.27	1.49	0.07	-0.42

Exploratory and Confirmatory Factor Analysis (EFA/CFA)

As this was a new survey, it is important to know whether participants are answering what we are designed to measure (hence whether the measurement instruments are valid) (Knekta et al., 2019). One approach is factor analysis, which examines the psychometric properties of the survey to ensure the items are robust and valid – meeting the researcher's intended interpretation and use. Factor analysis examines the relationship between survey items to determine whether participants' responses cluster into one subscale or another on the basis of measuring the same predefined construct (Mulaik, 1987). An exploratory factor analysis helps explore patterns underlying a data set, and a confirmatory factor analysis confirms the previously stated theoretical model by exploratory factor analysis.

Both an exploratory factor analysis (EFA) and confirmatory factor analysis (CFA) were conducted using *R studio* (R studio team, 2023) to examine the psychometric properties and initial factor structure of the survey items (i.e., beliefs, knowledge and frequency of activities) in measuring teachers' belief, knowledge and frequency of activities when teaching autistic children aged 7-11 years. Prior to the factor extraction, tests [i.e., Bartlett's test of Sphericity and Kaiser–Meyer–Olkin Measure of Sampling Adequacy (KMO)] were conducted to assess the suitability of the data for further factor analysis (Williams et al., 2010). Bartlett's test of Sphericity was conducted to examine the assumption of sphericity of the survey data, and it should be significant (p<.05) to continue analysing factor analysis (Hair et al., 1995). KMO was conducted to test the adequacy of the survey data (Hair et al., 1995). The KMO index ranged from 0 to 1, with 0.5 as a suitable indicator and 0.8 and above as a good indicator that the data could undergo factor analysis (Costales et al., 2022).

The number of factors that needed to be retained was determined if eigenvalues were greater than 1.0. Items contained within each factor were examined by thematic content to assign factor labels to the emergent factors. Factor matrix scores (scores > .50 or the score weighted most on factors) for each survey item were examined. Also, measurement invariance using Multiple Indicators Multiple Causes (MIMIC) models was examined. According to Brown, measurement invariance should satisfy the following, in order of importance: (a) equal factor structure, (b) equal factor loadings, (c) equal intercepts, and (d) equal indicator residuals. The final criterion could be hard to satisfy, so perhaps it is not necessary for acceptable measurement invariance (Brown, 2006). Five goodness-of-fit indices were assessed for the model fit: X^2 statistic, root mean square error of approximation (RMSEA), comparative fit index (CFI), Tucker-Lewis's index (TLI), Standardized Root Mean Square Residual (SRMR) and Akaike's information criterion (AIC). A good model fit would be a) CFI close to 0.90 or greater; b) TLI close to 0.90 or greater; c) RMSEA close to 0.06 or less; d) SRMR close to 0.08 or less; e) lowest AIC among model comparisons.

Two hypothesised measurement models would be tested in the belief, knowledge and frequency of activities section, respectively: 1) a uni-dimensional model (single factor – e.g., knowledge section); and 2) a three-factor model (e.g., knowledge: motor *vs* literacy *vs* maths skills). Model improvements would be based on the modification index (MI) and residual covariance matrix (i.e., examine survey items that the model may over- or underestimate to improve the model fit) using R studio. The largest MIs, a mathematically optimal parameter suggested as a modification by R, which might not also make reasonable sense, was considered in turn and only included based on a theoretical justification and inspection of the model residual

covariance matrix. Wood et al. (2007) found that the need to correlate residual covariances of items to achieve optimal reasons for shared residual variance could be due to similar item wording, shared method variance, or the existence of additional factors. The model was re-run iteratively after the largest MI and repeated on the second largest MI if the largest MI did not improve the model fit indices to an acceptable level or if the expected parameter changes (EPC) were small and not meaningful (Brown, 2006). The final best-fitting model is based on theory, parsimony and the best model indices.

Factor scores would be used for each survey item, as they gave a more accurate weighting of each survey item on its latent factor. Factor scores help us understand each participant's true factor score based on how they answered the survey. Notably, factor scores consider the varying influence of survey items by assigning higher factor loadings to more impactful items.

Correlation

Bivariate correlation analysis was performed on all variables, including demographic variables, beliefs, knowledge and frequency of activities. We include all the demographic variables to examine whether any of them may affect the DVs (i.e., belief, knowledge and frequency of activities of motor skills). Following Field (2017), a bivariate association of $r \geq 0.30$ would be considered as a moderate strength of association in the field of psychology and social sciences, which can inform the decision of whether to include certain variables (e.g., school type, beliefs and knowledge of literacy skills) in a hierarchical regression model to explore their unique contributions to dependent variables while controlling for other variables.

Hierarchical Multiple Regression

For hierarchical multiple regression, the initial regression steps involve the inclusion of demographic variables (e.g., school type and teaching years), followed by the augmentation of the model with the introduced factor scores. This hierarchical structure helps us understand how specific factors (e.g., belief of literacy and maths skills) and demographic variables independently contribute to explaining variations in the dependent variables (i.e., belief, knowledge and frequency of activities of motor skills).

Handling Missing Data

One of the most common issues in survey research is missing data (Brick & Kalton, 1996). Missing data in each section of the survey was less than 5% (e.g., accidentally missing one survey item within a section). Since the mean score of each section was used for analysis, this amount of missing data did not affect the results.

Results

ANOVA Analyses for Mean Differences

An ANOVA indicated that teachers' beliefs in motor, literacy and maths skills were statistically significant (F (2, 375) = 3.24, p = .04), indicating their beliefs were significantly different between these three skills (see Figure 4). The post-hoc least significant difference (Bonferroni) test showed that there was no statistical difference between motor and literacy skills (p = 1.00), motor and maths skills (p = .09) and literacy and maths skills (p = .08).

In terms of knowledge, the assumption of Levene's test of homogeneity of variance was violated (p <.001), so Welch ANOVA and a Games-Howell test for posthoc test would be used. The Welsh ANOVA yielded a statistically significant result (F (2, 229) = 10.69, p < .001), indicating that there are significant differences among teachers' knowledge of motor, literacy and maths skills. Based on post-hoc testing, teachers had more knowledge of motor skills than literacy skills (p = .01) and maths skills (p < .001). Also, teachers exhibited no difference between their knowledge of literacy and knowledge of maths skills (p =.09).

In terms of frequency of activities, ANOVA showed no significant differences between motor, literacy and maths skills (F (2, 339) = 1.16, p = .32). Post-hoc testing showed that there was no statistical difference between motor and literacy skills (p = .54), motor and maths skills (p = .60), and literacy and maths skills (p = 1.00).

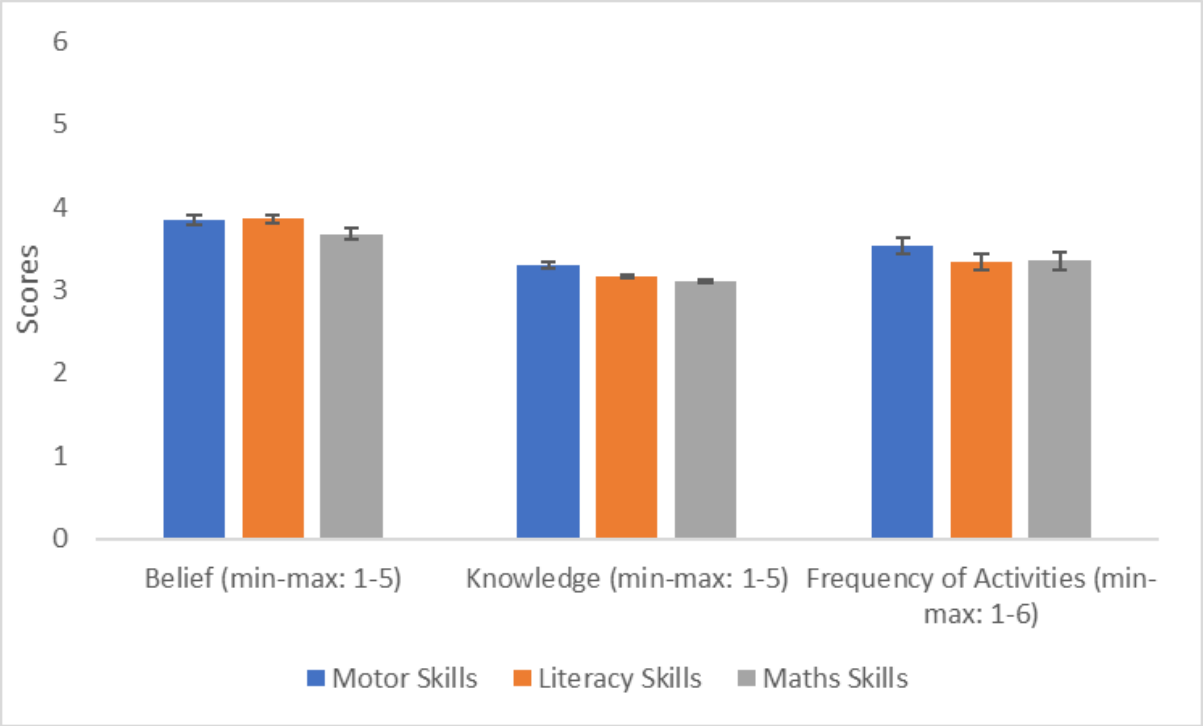

Figure 4. Mean score as a function of section and domain. Error bars represent standard error of the mean.

EFA &CFA

Knowledge scores were computed by summing all items for each domain (i.e., knowledge of motor, literacy and maths skills) after reverse coding items for the knowledge section with false answers. Before analysing the factor structure with EFA/CFA, we examine 1) the correlation matrix between survey items for the presence of correlation that exceeds .30 (Mukaka, 2012); 2) the appropriateness of the correlation matrix using tests such as Bartlett's test and Kaiser-Meyer-Olkin (KMO). As most of the inter-item correlation matrix contained absolute values greater than > 0.3, the correlational structure among these survey items enables us to extract latent variable (factors) for the survey model. In terms of the appropriateness of the correlation matrix, Bartlett's test was significant, indicating that the assumption of sphericity could be assumed, $\chi 2\ (809) = 324.17$, $p < .001$. Evidence of sampling

adequacy was found to be in the mediocre range (Kaiser–Meyer–Olkin, KMO = .65; Kaiser, 1974). Thus, the data appeared to be acceptable for the planned EFA on the 72-item survey [(i.e., beliefs (*n* = 18 items); knowledge (*n* = 30 items); frequency of activities (*n* = 24 items)].

3-Factor Model (with EFA):

Based on EFA, a 3-factor model was found containing: 1) beliefs, 17.5% of the variance; 2) knowledge, 14.3% of the variance; 3) frequency of activities, 8.4% of the variance. Factor loadings and communalities were reported, and Cronbach's α was conducted to assess the reliability of total scale scores and subscale scores (see Table 14).

In terms of motor skills knowledge, factor loadings were not consistent on one factor, suggesting that teachers may interpret the knowledge of motor skills survey items in diverse ways (see 2). An EFA analysis was further conducted to knowledge of motor skills. There were 3 factors extracted from the analysis. The first factor consists of survey items 2, 3, 6, 7 and 9; the second factor consists of survey items 1, 4 and 5; the third factor consists of survey items 8 and 10. Based on the thematic content and previous literature on knowledge of motor skills, the research group discussed and assigned labels for these 3 factors in knowledge of motor skills section. Survey items 2, 3, 6, 7 and 9, the first factor, were in general on the topic of motor processing (e.g., motor planning and execution). The theme for this factor was knowledge of motor processing. In terms of the second factor, survey items 1, 4 and 5 had similar factor loading. By examining the theme of these survey items, the

research group found that the items had similar question structure and wording (i.e., all start with “autistic and non-autistic children...”) and they did not have an obvious and consistent theme of the motor skills aspect. In terms of the third factor, survey items 8 and 10 were on the topic of playing computer games and copying. Teachers might interpret these items as not related to motor skills. Based on the discussion with S.H. and K.W. of the content, items 2, 3, 6, 7, and 9 represented teachers’ knowledge of motor processing skills.

3-Factor Model (with CFA):

Belief

An initial 3-factor model (belief of motor skills; belief of literacy skills and belief of maths skills) with modification (15 MIs) showed an adequate fit to the *belief* data ($\chi 2$ (d.f.) = 237.28(117), p <.001, CFI/TLI = 0.90/0.86, RMSEA = 0.090 (90% CI 0.074–0.107), p = 0.85, SRMR = 0.06) (see Table 14). Based on the residual covariance matrix, one survey item from belief of motor skills (i.e., ‘*When learning motor skills like netball or cricket, autistic children also learn social skills like nonverbal communication such as eye contact and gestures.’*) and one survey item from belief of maths skills (i.e., ‘*When learning maths skills like comparing objects (e.g., “point to tallest and shortest plants”), autistic children also learn language and daily living skills like recognising words and signs in daily life.’*) had high covariance value with most other belief items [exceed the variance threshold (variance value: 2)], suggesting that the model underestimated these two items. These two survey items were removed after examining their theoretical meaning. After removing these two items, the modified 3factor model with modification (8 MIs) showed a better fit to the *belief* data ($\chi 2$ (d.f.) = 137.93(77), p <.001, CFI/TLI = 0.93/0.90, RMSEA = 0.079 (90% CI 0.057–0.100), p =

0.02, SRMR = 0.05). This modified model would be used to administer belief data in further analysis, as it was a more parsimonious 'simpler' model. Future studies would check on the effect of removing these two items and should still administer both items and see whether there would be any differences for other participant groups.

Knowledge

An initial 3-factor model (knowledge of motor skills, knowledge of literacy skills and knowledge of maths skills) with modification (8 MIs) showed an inadequate fit to the *knowledge* data ($\chi 2$ (d.f.) = 546.86(264), p <.001, CFI/TLI = 0.82/0.79, RMSEA = 0.094 (90% CI 0.083–0.106), p= 0.98, SRMR = 0.08) (see Table 14). Based on the residual covariance matrix, three survey items from knowledge of literacy skills (e.g., '*Autistic children are typically expected to use language in various situations in Key Stage 2, such as drama, formal presentations, and debate.'*) and three survey items from knowledge of maths skills (e.g., *'Autistic children are typically expected to learn about using and interpreting algebraic notation in Key Stage 2, including 3y in place of y + y + y and 3 × y.)* had high covariance value with most of the other knowledge items [exceed the variance threshold (variance value: 2)], suggesting the model underestimated these items. After removing these six items, the modified 3-factor model with modification (7 MIs) showed an acceptable fit to the *knowledge* data ($\chi 2$ (d.f.) = 221.23(142), p <.001, CFI/TLI = 0.92/0.90, RMSEA = 0.068 (90% CI 0.05–0.085), p = 0.04, SRMR = 0.07). This modified model would be used to administer knowledge data in further analysis, as it was a more parsimonious 'simpler' model. Future studies would check on the effect of removing these two items and should still administer both items and see whether there would be any differences for other participant groups.

Frequency of Activities

An initial 3-factor model (frequency of activities: motor skills, literacy skills and maths skills) with modification (8 MIs) showed an inadequate fit to the *frequency of activities* data ($\chi 2$ (d.f.) = 441.55(241), p <.001, CFI/TLI = 0.83/0.81, RMSEA = 0.085 (90% CI 0.073–0.098), p = 0.77, SRMR = 0.09) (see Table 14). Based on the residual covariance matrix, two survey items from frequency of activities of motor skills (e.g., '*Autistic children play alone in the playground, such as jumping on trampoline, swing on a swing, or riding scooter.')*, one survey item from frequency of activities of literacy skills (e.g., *Autistic children share their opinions about a book, such as why they like a particular poem.*) and one survey item from frequency of activities of maths skills (e.g., *'Autistic children use educational software or apps to learn about maths, such as Topmarks, or Number Bombs.)* had a high covariance value with most of the other frequency of activities items [exceed the variance threshold (variance value: 2)], suggesting the model underestimated these items. After removing these four items, the modified 3-factor model with modification (6 MIs) showed an acceptable fit to the *frequency of activities* data ($\chi 2$ (d.f.) = 235.16(161), p <.001, CFI/TLI = 0.92/0.90, RMSEA = 0.064 (90% CI 0.045–0.081), p = 0.11, SRMR = 0.07). This modified model would be used to administer frequency of activities data in further analysis, as it was a more parsimonious 'simpler' model. Future studies would check on the effect of removing these two items and should still administer both items and see whether there would be any differences for other participant groups.

Further data analysis (i.e., bivariate correlation and hierarchical regression) on teachers' belief, knowledge and frequency of activities would use the modified models based on CFA results, using factor scores.

Table 14 Exploratory and confirmatory factor analysis models of beliefs, knowledge and frequency of activities on motor, literacy and maths skills							
Model	χ2 (d.f.)	CFI	TLI	RMSEA (90% CI)	*p*	SRMR	AIC (χ2–2d.f.)
Belief							
1. Single factor	321.45 (135)	0.84	0.82	0.105 (0.090-0.119)	1.00	0.07	4894.21
2. Three factors Belief_Motor Belief_Literacy Belief_Maths	318.17 (132)	0.84	0.81	0.106 (0.091-0.121)	1.00	0.07	4896.93
Model modifications							
M1. Three factors LiteracyQ2 with Literacy Q3	304.31 (131)	0.85	0.82	0.102 (0.087-0.118)	0.99	0.07	4885.08
M2. Three factors MathsQ1 with MathsQ2	292.80 (130)	0.86	0.83	0.100 (0.085-0.115)	0.98	0.06	4875.57
M3. Three factors LiteracyQ1 with LiteracyQ6	284.63(129)	0.86	0.84	0.098 (0.083-0.113)	0.97	0.06	4869.40
M4. Three factors LiteracyQ3 with LiteracyQ6	280.67(128)	0.87	0.84	0.097 (0.082-0.113)	0.97	0.06	4867.43

M5. Three factors MotorQ2 with MotorQ4	272.84(127)	0.87	0.85	0.095 (0.080-0.111)	0.95	0.06	4861.60
M6. Three factors LiteracyQ1 with LiteracyQ3	264.44(126)	0.88	0.85	0.093 (0.078-0.109)	0.92	0.06	4855.20

M7. Three factors MotorQ3 with MotorQ4	258.80(125)	0.88	0.86	0.092 (0.076-0.108)	0.90	0.06	4851.57
M8. Three factors MathsQ1 with MathsQ6	254.96(124)	0.89	0.86	0.092 (0.076-0.108)	0.89	0.06	4849.72
M9. Three factors MotorQ4 with MotorQ5	252.77(123)	0.89	0.86	0.092 (0.075-0.108)	0.88	0.06	4849.53
M10. Three factors LiteracyQ4 with LiteracyQ5	250.22(122)	0.89	0.86	0.091 (0.075-0.107)	0.88	0.06	4848.99
M10. Three factors LiteracyQ4 with LiteracyQ5	250.22(122)	0.89	0.86	0.091 (0.075-0.107)	0.88	0.06	4848.99
M11. Three factors MathsQ3 with MathsQ6	246.22(121)	0.89	0.86	0.091 (0.075-0.107)	0.87	0.06	4847.69
M12. Three factors MotorQ2 with MotorQ3	243.68(120)	0.89	0.86	0.090 (0.074-0.107)	0.86	0.06	4846.44

M13. Three factors MotorQ1 with MotorQ3	241.75(119)	0.89	0.86	0.090 (0.074-0.107)	0.86	0.06	4846.51
M14. Three factors MathsQ1 with MathsQ3	239.17(118)	0.89	0.86	0.090 (0.074-0.107)	0.85	0.06	4845.93
M15. Three factors MotorQ5 with MotorQ6	237.28(117)	**0.90**	0.86	0.090 (0.074-0.107)	0.85	0.06	4846.04

Residual Matrix							
Three factors (without motorQ1 & maths Q6)	225.56 (101)	0.87	0.84	0.099(0.082-0.116)	0.96	0.06	4430.30
Modification Indices based on Residual Matrix							
M1a. Three factors MathsQ1 with MathsQ2	187.27 (86)	0.88	0.85	0.097 (0.078-0.116)	0.93	0.06	4198.59
M2a. Three factors LiteracyQ2 with LiteracyQ3	175.77 (85)	0.89	0.87	0.092 (0.073-0.111)	0.85	0.06	4189.08
M3a. Three factors MotorQ2 with MotorQ4	165.12 (84)	**0.90**	0.88	0.088 (0.068-0.107)	0.75	0.06	4180.43
M4a. Three factors LiteracyQ2 with LiteracyQ5	160.97 (83)	**0.91**	0.88	0.086 (0.066-0.106)	0.71	0.06	4178.29

M5a. Three factors MotorQ3 with MotorQ4	152.58 (82)	**0.92**	0.89	0.083 (0.062-0.103)	0.60	0.06	4171.89
M6a. Three factors MotorQ4 with MotorQ5	150.80 (81)	**0.92**	0.89	0.083 (0.062-0.103)	0.60	0.06	4172.11
M7a. Three factors LiteracyQ1 with LiteracyQ3	144.97 (80)	**0.92**	**0.90**	0.080 (0.059-0.101)	0.53	0.05	4168.29
M8a. Three factors LiteracyQ1 with LiteracyQ5	141.23 (79)	**0.93**	**0.90**	0.079 (0.057-0.100)	**0.02**	0.05	4166.54
M9a. Three factors MotorQ2 with MotorQ3	139.13 (78)	**0.93**	**0.90**	0.079 (0.057-0.100)	**0.02**	0.05	4166.43
M10a. Three factors MotorQ3 with MotorQ6	137.93 (77)	**0.93**	**0.90**	0.079 (0.057-0.100)	**0.02**	0.05	4167.24
Knowledge							
1a. Single factor	1093.95(405)	0.60	0.57	0.119 (0.111-0.128)	1.00	0.103	8785.18
1b. Single factor with Knowledge_Motor processing (only 5 questions)	846.60 (275)	0.63	0.60	0.132 (0.122-0.142)	1.00	0.107	7181.94

2. Two factors Knowledge_Literacy Knowledge_Maths	499.59 (169)	0.77	0.74	0.128 (0.115-0.141)	1.00	0.09	5436.43
3a. Three factors Knowledge_Motor Knowledge_Literacy Knowledge_Maths	951.35 (402)	0.68	0.66	0.107 (0.098-0.115)	1.00	0.109	8648.574
3b. Three factors Knowledge_MotorProcessing (with 5 questions) Knowledge_Literacy Knowledge_Maths	661.45 (272)	0.75	0.73	0.109 (0.099-0.120)	1.00	0.09	7002.786
Model modifications							
M1. Three factors MathsQ7 with MathsQ10	625.49 (271)	0.77	0.75	0.104 (0.094-0.115)	1.00	0.09	6883.28
M2. Three factors MathsQ9 with MathsQ10	607.90 (270)	0.78	0.76	0.102 (0.091-0.113)	1.00	0.09	6953.23
M3. Three factors MathsQ1 with MathsQ2	590.36(269)	0.79	0.77	0.100 (0.089-0.111)	1.00	0.09	6937.69
M4. Three factors MathsQ6 with MathsQ10	587.13(268)	0.80	0.77	0.100 (0.089-0.111)	1.00	0.09	6936.47

M5. Three factors MathsQ8 with MathsQ10	579.94 (267)	0.80	0.78	0.099 (0.088-0.110)	1.00	0.09	6931.27
M6. Three factors MathsQ3 with MathsQ7	559.31 (266)	0.81	0.79	0.096 (0.085-0.107)	0.99	0.09	6912.65
M7. Three factors MathsQ6 with MathsQ8	552.48(265)	0.82	0.79	0.095 (0.084-0.106)	0.99	0.08	6907.81
M8. Three factors MathsQ5 with MathsQ6	546.86(264)	0.82	0.79	0.094 (0.083-0.106)	0.98	0.08	6904.19
Residual Matrix							
Three factors (without literacyQ1, Q3 & Q4; MathsQ6, Q7 &Q10)	264.24 (149)	0.88	0.86	0.080(0.064-0.096)	0.52	0.07	5412.59
Modification indices based on Residual Matrix							
M1a. Three factors MathsQ1 with MathsQ2	248.60 (148)	0.89	0.88	0.075(0.059-0.091)	**0.01**	0.07	5398.95
M2a. Three factors LiteracyQ2 with LiteracyQ6	242.49 (147)	**0.90**	0.88	0.094(0.057-0.090)	**0.01**	0.07	5394.84
M3a. Three factors MathsQ3 with MathsQ8	236.87 (146)	**0.90**	0.89	0.072(0.055-0.088)	**0.02**	0.07	5391.22

M4a. Three factors MathsQ2 with MathsQ5	232.28 (145)	**0.91**	0.89	0.071(0.053-0.087)	**0.03**	0.07	5388.63
M5a. Three factors MotorQ6 with MotorQ7	228.46 (144)	**0.91**	0.89	0.070(0.052-0.087)	**0.03**	0.07	5386.81
M6a. Three factors LiteracyQ7 with LiteracyQ10	225.12 (143)	**0.91**	**0.90**	0.069(0.051-0.086)	**0.04**	0.07	5385.47
M7a. Three factors MathsQ2 with MathsQ3	221.23 (142)	**0.92**	**0.90**	0.068(0.050-0.085)	**0.04**	0.07	5383.58
Frequency of activities (FoA)							
1. Single factor	599.91 (252)	0.71	0.68	0.110 (0.099-0.121)	1.00	0.09	9408.84
2. Three factors FoA_Motor FoA_Literacy FoA_Maths	533.08 (249)	0.76	0.74	0.100 (0.088-0.111)	0.99	0.09	9346.01
Model modifications							
M1. Three factors LiteracyQ6 with LiteracyQ8	506.06 (248)	0.79	0.76	0.096 (0.084-0.107)	0.98	0.09	9322.99

M2. Three factors LiteracyQ2 with LiteracyQ6	493.36 (247)	0.80	0.77	0.094 (0.081-0.106)	0.97	0.09	9312.29
M3. Three factors MotorQ1 with MotorQ6	479.17(246)	0.81	0.78	0.091 (0.079-0.103)	0.94	0.09	9300.10
M4. Three factors MathsQ1 with MathsQ2	466.48(245)	0.82	0.79	0.089 (0.077-0.101)	0.89	0.09	9289.41
M5. Three factors MotorQ6 with MotorQ7	456.75(244)	0.82	0.80	0.087 (0.075-0.100)	0.84	0.09	9281.68
M6. Three factors LiteracyQ4 with LiteracyQ8	453.04(243)	0.83	0.80	0.087 (0.075-0.100)	0.83	0.09	9279.97
M7. Three factors MotorQ3 with MotorQ8	446.22(242)	0.83	0.81	0.086 (0.073-0.098)	0.79	0.09	9275.15
M8. Three factors LiteracyQ5 with LiteracyQ6	441.55 (241)	0.83	0.81	0.085(0.073-0.098)	0.77	0.09	9272.48
Residual Matrix							
Three factors (without motor Q1 & Q6; literacy Q8; maths Q1)	285.34 (167)	0.87	0.85	0.079(0.063-0.063)	**0.002**	0.08	7759.71

Modification indices based on Residual Matrix							
M1a. Three factors LiteracyQ5 with LiteracyQ6	270.42 (166)	0.88	0.87	0.074(0.058-0.090)	**0.01**	0.07	7746.79
M2a. Three factors LiteracyQ2 with LiteracyQ6	259.83 (165)	0.89	0.88	0.071(0.054-0.087)	**0.02**	0.07	7738.20
M3a. Three factors MotorQ4 with MotorQ7	250.66 (164)	**0.90**	0.89	0.068(0.051-0.084)	**0.04**	0.07	7731.20
M4a. Three factors MotorQ3 with MotorQ8	250.66 (163)	**0.91**	**0.90**	0.066(0.048-0.082)	0.07	0.07	7725.79
M5a. Three factors MotorQ5 with MotorQ8	237.62 (162)	**0.92**	**0.90**	0.064(0.046-0.081)	0.10	0.07	7721.98
M6a. Three factors MotorQ3 with MotorQ5	235.16 (161)	**0.92**	**0.90**	0.064(0.045-0.081)	0.11	0.07	7721.79

Bivariate Correlations

Prior to hierarchical multiple regression analysis, bivariate correlations of were conducted to assess the strength and direction of relationships between individual pairs of variables. Predictors for the further regression analysis were determined based on whether the correlations with the dependent variables are significant and if they align with the previous literature. Inter-factor correlations between three factors (i.e., beliefs vs knowledge, belief vs frequency of activities, knowledge vs frequency of activities) were .01, .40 and -.05, respectively. Only belief and frequency of activities were significantly positively correlated (r = .40). Further correlation analyses were conducted on subscales (i.e., beliefs, knowledge, and frequency of activities of motor skills, literacy, and maths skills) (see Table 15.1), as well as demographic information to determine predictors for further regression analysis (see Table 15.2).

As expected, all three subscales of beliefs (i.e., beliefs of motor, literacy, and maths skills) were significantly correlated (r range from 0.46 to 0.83), suggesting that teachers' beliefs in motor, literacy and maths skills had a moderate to strong positive relationship with each other. Teachers' beliefs in motor are positively correlated with their beliefs in maths (r = .83). All three subscales of frequency of activities (i.e., frequency of activities of motor, literacy, and maths skills) were also significantly correlated (r range from 0.62 to 0.69), suggesting that teachers' frequency of activities in motor, literacy and maths skills had a strong positive relationship with each other. In terms of knowledge, knowledge of literacy and maths skills were significantly correlated (r = 0.75), suggesting a strong positive relationship. Knowledge of motor skills was not significantly correlated with other knowledge factors, suggesting the knowledge section was singular. Knowledge of motor skills was significantly correlated with *beliefs* of motor skills (r =.23), suggesting a weak positive relationship.

As shown in Table 15.2, predicting variables that were significantly correlated with the dependent variables (i.e., beliefs, knowledge and frequency of activities of motor skills) would be entered into the regression model. In terms of beliefs of motor skills, the correlated and predicting variables for regression analysis were belief of literacy skills (r = .52) and maths skills (r = .83), knowledge of motor skills (r = .23), frequency of activities of literacy skills (r = .29) and maths skills (r = .34). In terms of knowledge of motor skills, the correlated and predicting variables for regression analysis were living area (r = .21), belief of motor skills (r = .23) and frequency of activities of maths skills (r = .25). In terms of frequency of activities of motor skills, the correlated and predicting variables for regression analysis were: school type (r = .23), teaching experience (r = .20), SEN training (r = -.22), maths training (r = -.21), literacy training (r = -.22), belief of literacy skills (r = .20) and maths skills (r = .23), knowledge of maths skills (r = .19), frequency of activities of literacy skills (r = .67) and maths skills (r = .67).

Table 15.1 Bivariate correlations of belief, knowledge and frequency of activities of motor, literacy and maths skills

	1	2	3	4	5	6	7	8	9
1.Belief Motor	--								
2.Belief Literacy	.52***	--							
3.Belief Maths	.83***	.46***	--						
4.Knowledge Motor	.23*	.16	.16	--					
5.Knowledge Literacy	-.04	.02	.05	-.08	--				
6.Knowledge Maths	.06	.16	.07	-.09	.75***	--			
7.FoA Motor	.16	.20**	.28***	.05	-.13	.16	--		
8.FoA Literacy	.29***	.23**	.29***	.13	.14	-.22**	.62***	--	
9.FoA Maths	.34***	.29**	.38***	.25**	.04	-.04	.68***	.69***	--

* p<.05, ** p<.01, *** p<.001. FoA – frequency of activities

Table 15.2 Bivariate correlations of demographic information, belief, knowledge and frequency of activities of motor, literacy and maths skills

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1. Gender	--																				
2. Age group	.06	--																			
3. Degree	.04	-.04	--																		
4. Ethnicity	-.06	-.02	.03	--																	
5. Living area	.07	-.17	.05	.31**	--																
6. School type	-.09	.23*	-.12	-.01	-.28**	--															
7. Job role	-.14	.06	.08	-.05	-.09	-.15	--														
8. Teaching experience	-.07	.71**	-.18	-.07	-.24**	.37**	.07	--													
9. SEN training	.06	-.34**	.07	.19*	.31**	-.49**	.21*	-.56**	--												
10. Motor training	.01	-.23**	.04	.17	.21*	-.35**	.08	-.34**	.55**	--											
11. Maths training	-.18	-.24**	.06	.03	.24*	-.36**	.15	-.36**	.54**	.49**	--										
12. Literacy training	-.09	-.31**	.06	.07	.23*	-.50**	.18	-.50**	.61**	.49**	.80**	--									
13. Belief Motor	-.07	.16	-.15	.12	.08	.12	-.15	.15	-.14	-.07	-.14	-.06	--								
14. Belief Literacy	.07	.17	-.16	.09	.04	.22*	-.14	.17	-.21*	-.15	-.15	-.07	.52**	--							
15. Belief Maths	.01	.06	-.04	.03	-.03	-.004	-.16	-.03	.09	.04	-.01	-.01	.83**	.46**	--						
16. Knowledge Motor	-.02	-.11	-.13	.07	.21*	.03	.02	-.07	.09	.10	-.01	-.01	.23*	.16	.16	--					
17. Knowledge Literacy	.04	.19*	-.06	.04	-.02	.20*	.06	.02	-.11	-.02	.10	.05	.06	.16	.07	-.09	--				
18. Knowledge Maths	.04	.23*	.07	.14	-.12	.28**	.11	.11	-.06	-.08	-.02	-.07	-.04	.02	.05	-.08	.75**	--			
19. FoA Motor	.03	.14	-.04	.13	-.09	.23*	-.03	.20*	-.22*	-.17	-.21*	-.22*	.16	.20*	.28**	.05	.19*	.16	--		
20. FoA Literacy	.13	.03	-.03	.04	.02	-.07	-.23*	.08	-.19*	-.13	-.27**	-.20*	.29**	.29**	.23*	.13	-.18	-.22*	.62**	--	
21. FoA Maths	.01	.06	-.07	.04	.05	.06	-.10	.12	-.10	-.12	-.14	-.13	.34**	.23**	.29**	.25**	-.01	-.04*	.68**	.69**	--

* p<.05, ** p<.01, *** p<.001. FoA – frequency of activities

Hierarchical Multiple Regression

Hierarchical regression was conducted to explore predictors (e.g., school types and SEN training) of teachers' beliefs, knowledge and frequency of activities in motor skills (DV). Various groups of IVs (i.e., demographic information; belief; knowledge and frequency of activities) were inserted at different steps to examine whether demographic information, beliefs, knowledge or frequency of activities were the key predictor of the dependent variables. Data were also screened for meeting assumptions of hierarchical multiple regression including: 1) independence of residuals (Durbin–Watson statistic of 2.18), 2) multivariate outliers/influential data points, 3) multicollinearity, 4) normality of residuals, and 5) homoscedasticity of residuals, with no major violations observed. When examining multicollinearity among the underlying (predicting) variables, some IVs are highly correlated with other IVs, resulting in the invalidity of regression results. In this study, literacy training was highly correlated with literacy training (r = .80) and SEN training (r =. 61). Nonetheless, these variables are measuring different aspects so would still be analysed in the regression model.

To examine the effect of different teachers' sections (i.e., beliefs, knowledge and frequency of activities) and which section accounts for the most variance for each dependent variable, the sections were examined in different orders using hierarchical regression. Model 1 includes demographic information only, while Models 2, 3 and 4 tested six different permutations:

1. beliefs-knowledge-frequency of activities
2. knowledge-beliefs-frequency of activities

3. beliefs-frequency of activities-knowledge

4. knowledge-frequency of activities-beliefs
5. frequency of activities-beliefs-knowledge
6. frequency of activities-knowledge-beliefs

In terms of beliefs and knowledge of motor skills, the model sequence analyses suggested that beliefs account for the most variance, and frequency of activities accounts for the least variance. The model sequence for beliefs and knowledge of motor skills is *beliefs – knowledge – frequency of activities*, which will be reported in the following sections. In terms of frequencies of activities of motor skills, the model sequence analyses suggested that frequency of activities accounts for the most variance, and beliefs accounts for the least variance. The model sequence for frequency of activities of motor skills is *frequency of activities – knowledge – beliefs*, which will be reported in the following sections.

Beliefs of motor skills

Prior to conducting the hierarchical regression analysis, outliers were identified based on the criterion of standardised residuals exceeding ±2.0, using three outlier analysis (i.e., Mahalanobis Distance, Cook's Distance and Centred Leverage Value). Case 98 was identified as an outlier based on the criterion. Sensitivity analyses were conducted with and without the outlier to check on its impact on the regression coefficients. There was no big difference to the result whether the outlier was included

or excluded. Thus, hierarchical regression analyses will continue without deletion of the outlier.

A summary of the hierarchical regression analyses with three models predicting *beliefs* in motor skills was provided in Table 16a. Model 1, which included beliefs of literacy and maths skills, was significant ($F(2,111) = 132.30$, $p < .001$, $R^2 = .71$). Model 2, which included knowledge in motor skills, was significant ($F(1, 110) = 90.51$, $p < .001$, $R^2 = .71$). The addition of knowledge as a predictor was not significant and only explained an additional 1% variance ($\Delta R^2 = 0.01$, $p = .10$). Model 3 as a whole (additionally including frequency of activities in motor and literacy skills) was significant ($F(2, 108) = 57.74$, $p < .001$, $R^2 = .73$). The addition of frequency of activities of motor and literacy skills as predictors was significant and only explained an additional 2% variance ($\Delta R^2 = 0.02$, $p = .045$).

In terms of the predictors of beliefs in motor skills, belief in maths was found to be the strongest predictor in this analysis, exhibiting a high unstandardised coefficient of 0.75 ($p < .001$), and signifies a strong effect size ($\beta = 0.75$). This underscores the statistically significant association in beliefs between maths and motor skills. Beliefs in literacy skills, while statistically significant with an unstandardised coefficient of 0.15 ($p = .005$), demonstrated a weaker influence ($\beta = 0.16$). Furthermore, frequency of activities of motor activities presented a negative unstandardised coefficient of - 0.16 ($p = .016$), indicating that increased frequency of activities in motor skills resulted in lower beliefs in motor skills ($\beta = 0.16$). These findings collectively underscore the multidimensional nature of belief formation in motor skills, that teachers' beliefs in maths skills predict their beliefs in motor skills the most in this analysis.

Table 16a. Summary of predictors on beliefs in motor skills using hierarchical regression.

Beliefs in motor skills	Model 1				Model 2				Model 3			
	B (SE)	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*
Beliefs in literacy skills	** **.16 (.06)**	.17	2.98	.06, .27	** **.15 (.06)**	.16	2.82	.05, .26	** **.15 (.05)**	.16	2.86	.05, .26
Beliefs in maths skills	*** **.75 (.06)**	.75	12.83	.64, .87	*** **.75 (.06)**	.74	12.72	.63, .86	*** **.75 (.06)**	.75	12.77	.64, .87
Knowledge in motor skills					.09 (.06)	.09	1.66	-.02, .21	.08 (.06)	.08	1.50	-.03, .19
Frequency of activities in motor skills									.13 (.07)	.13	1.95	-.002, .26
Frequency of activities in literacy skills									-.16 (.07)	-.16	-2.44	-.29, .03
R	.84				.84				.85			
R²	.70				.71				.73			

Adjusted R²	.70	.70	.72
SE	.52	.51	.50

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∆ R²	.70	.01	.02
F	132.30	90.51	57.74
∆F	132.30	2.76	3.19
df1	2	1	2
df2	111	110	108

*p<.05 **p<.01 ***p<.001

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Knowledge of motor skills as dependent variable

A summary of the hierarchical regression analyses with three models predicting *knowledge* in motor skills was provided in Table 16b. Model 1, which included living area, was significant (F (1,112) = 5.14, *p* =.03, R^2 = .05). Model 2, which included belief in motor skills, was significant (F (1, 111) =5.41, *p* = .01, R^2 = .09). The addition of belief in motor skills as predictor was significant and explained an additional 5% variance (ΔR^2 = 0.05, p = .02). Model 3 as a whole (additionally including frequency of activities in maths skills) was significant (F (1, 110) =4.95, p = .003, R^2 = .12). The addition of frequency of activities of maths skills as the predictor was not significant and only explained an additional 3% variance (ΔR^2 = 0.03, p = 0.06).

In terms of predictors of knowledge in motor skills, living area was found to be the only significant predictor in this analysis, exhibiting the unstandardised coefficient of 0.8 (*p* = .04) and signifying a weak effect size (β = 0.19). This suggested that teachers who live in other areas have better knowledge in motor skills than teachers who live in English. Nonetheless, 94 of 114 teachers had reported that they lived in English. This could result in unreliability of this finding. Frequency of activities in maths skills, while statistically not significant, has a tendency to be significant (*p* = .06). The overall variance of the model is 35%, suggesting that other unmeasured factors may influence teachers' knowledge of motor skills. Further studies with more factors should be used to analyse the predictors of knowledge of motor skills.

Table 16b. Summary of predictors on knowledge in motor skills using hierarchical regression.

Knowledge in motor skills	Model 1				Model 2				Model 3			
	B (SE)	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*	*B (SE)*	*β*	*t*	*95% CI B*
Living area	* **.08 (.04)**	.21	2.27	.01, .26	* **.08 (.04)**	.19	2.13	.01, .15	* **.08 (.04)**	.19	2.11	.01, .15
Belief in motor skills					* **.20 (.08)**	.21	2.34	.03, .36	.24 (.09)	.15	1.56	-.04, .31
Frequency of activities of maths skills									.17 (.09)	.18	1.94	-.004, .35
R	.21				.30				.35			
R²	.04				.09				.12			
Adjusted R²	.04				.07				.10			
SE	.86				.84				.83			
∆ *R²*	.04				.05				.03			
F	5.14				5.41				4.95			
∆ *F*	5.14				5.47				3.76			

df1	1	1	1
df2	112	111	110

*p<.05 **p<.01 ***p<.001

Frequency of activities of motor skills as dependent variable

A summary of the hierarchical regression analyses with four models predicting frequency of activities of motor skills was provided in Table 16c. In Model 1, which included demographic information (e.g., school type, teaching experience and whether participants receive SEN training), living area was not significant ($F(5,108) = 1.93$, $p = .10$, $R^2 = .08$). Model 2, which included frequency of activities of literacy and maths skills, was significant ($F(2, 106) = 18.86$, $p < .001$, $R^2 = .56$). The addition of frequency of activities of literacy and maths skills as predictors was significant and explained an additional 47% variance ($\Delta R^2 = 0.47$, $p < .001$). Model 3, which included knowledge of maths skills, was significant ($F(1, 105) = 19.32$, $p < .001$, $R^2 = .60$). The addition of knowledge of maths skills as predictor was significant and explained an additional 4% variance ($\Delta R^2 = 0.04$, $p = .002$). Model 4 as a whole (additionally including beliefs in literacy and maths skills) was significant ($F(2, 103) = 15.32$, $p < .001$, $R^2 = .60$). The addition of beliefs in literacy and maths skills as predictors was not significant and explained an additional 0.3% variance ($\Delta R^2 = 0.003$, $p = .72$).

In terms of predictors of frequency of activities of motor skills, school type was found to be a significant predictor, exhibiting the unstandardised coefficient of 0.17 ($p = .03$) and signifying a weak effect size ($\beta = 0.18$). This suggested that SEN teachers have a higher frequency of activities of motor skills than mainstream teachers. Frequency of activities in literacy and maths skills were both strong predictors for frequency of activities of motor skills with the unstandardised coefficient of 0.41 ($\beta = 0.41$, $p < .001$) in literacy and 0.29 ($\beta = 0.41$, $p < .001$) in maths skills. This finding indicates that increased frequency of activities in both literacy and maths skills has a positive impact on increasing frequency of activities motor skills. Knowledge of maths skills was also significantly predicting frequency of activities of motor skills ($\beta = 0.22$,

p = .002) with an unstandardised coefficient of 0.21. This suggested that increased knowledge of maths skills is positively associated with increased frequency of activities in motor skills.

Table 16c. Summary of predictors on frequency of activities in motor skills using hierarchical regression.

Frequency of Activities in Motor Skills	Model 1				Model 2				Model 3				Model 4			
	B	*β*	*t*	95% CI	*B*	*β*	*t*	95% CI	*B* (SE)	CI	*B* (SE)	*B*	(SE)	CI	*B* (SE)	*B*
School type	.13 (.10)	.14	1.29	-.07, .32	**.21 (.07)	.23	2.92	.07, .36	*.16 (.07)	.17	2.22	.02, .30	*.17 (.07)	.18	2.27	.02, .31
Teaching experience	.05 (.08)	.08	.67	-.10, .21	.04 (.06)	.06	.68	-.07, .15	.03 (.05)	.05	.58	-.08, .14	.03 (.06)	.05	.61	-.08, .14
SEN training	-.07 (.25)	-.04	-.29	-.56, .42		.02	.16	-.32, .38	.004 (.17)	.002	.02	-.33, .34	.001 (.18)	.001	.01	-.35, .35
Maths training	-.15 (.28)	-.08	-.55	-.71, .40	.10 (.20)	.05	.48	-.30, .49	.09 (.19)	.05	.47	-.29, .47	.08 (.20)	.04	.40	-.31, .46
Literacy training	-.08 (.30)	-.04	-.25	-.66, .51	-.03 (.21)	-.02	-.55	-.44, .38	-.03 (.20)	-.01	-.12	-.42, .37	-.003 (.21)	-.002	-.02	-.41, .41
Frequency of activities of literacy skills					***.35 (.10)	.35	3.66	.16, .54	***.40 (.09)	.41	4.33	.22, .58	***.41 (.09)	.41	4.35	.22, .59
Frequency of activities of maths skills					***.41 (.09)	.42	4.59	.23, .58	***.38 (.09)	.39	4.40	.21, .55	***.39 (.09)	.41	4.43	.22, .67

Knowledge of maths skills			**.21 (.06)	.22	3.25	.08, .33	**.21 (.07)	.22	3.26	.08, .34

Belief in maths skills							-.04 (.08)	-.04	-.52	-.19, .11
Belief in literacy skills							-.02 (.07)	-.02	-.33	-.16, .11
R	.29		.75			.77			.77	
R²	.08		.56			.60			.60	
Adjusted R²	.04		.53			.57			.56	
SE	.90		.63			.60			.61	
Δ *R²*	.08		.47			.04			.003	
F	1.93		56.23			19.32			15.32	
Δ *F*	1.93		56.23			10.59			.33	
df1	5		2			1			2	
df2	108		106			105			103	

*p<.05 **p<.01 ***p<.001

Discussion

The current study investigated teachers' beliefs, knowledge and frequency of activities in motor skills for autistic children aged 7 to 11 years in mainstream and special education needs (SEN) schools in the United Kingdom. A newly developed 72-item teacher-reported questionnaire on teachers' beliefs and knowledge and implementation of motor skills in schools and other subject areas demonstrated good psychometric properties. Study findings can inform teacher provision on supporting autistic children and the UK national curriculum guidelines, and each are discussed in turn below.

Exploratory and Confirmatory Factor Analysis (EFA/CFA) testing the psychometric properties of the newly developed survey resulted in three factors: belief, knowledge and frequency of activities. Each factor had three skills: motor, literacy and maths skills. The correlation of these three factors showed that these factors had small to medium relationships between them. Belief and frequency of activities were positively correlated though with a medium relationship between these two factors. Teachers' belief might affect their classroom practice, which is aligned with the findings from the previous literature (Brickhouse, 1990; Cheung, 2012)

First, teachers reported varying degrees of knowledge in motor skills, and they reported consistently on knowledge of literacy and maths skills. This finding suggested that teachers didn't know or did not have motor skills training or knowledge. They could answer the survey questions based on their experience with the autistic children they have worked with, or it could be that they were not sure which activities were motor skills related or not. By experience, teachers may understand motor skills as other

more common skills observed and discussed in the school setting, such as daily living skills (e.g., using knives and forks to eat, tying shoelaces). Lindsay (2007) suggested that SEN schools might focus on development of different skills (e.g., daily living skills; social skills) for children with special needs, instead of academic skills (e.g., literacy and maths skills). Teachers might have knowledge of various general skills in autistic children rather than just one singular skill. Also, only 22% of teachers had any form of motor skills training. This finding was consistent with Maher & Fitzgerald (2020), suggesting that teachers from SEN schools lack appropriate motor skills-related training. Thus, it is important to offer more motor-related practices to teaching staff from both mainstream and SEN schools.

A second finding was that teachers placed greater importance on beliefs in motor skills than in maths skills – there was no significant difference between motor and literacy skills. This finding was not in line with our hypothesis, which was that teachers' beliefs in literacy and maths skills would have greater importance than their beliefs in motor skills. Teachers were required to reach certain goals in literacy (e.g., read fluently and write accurately and coherently) and maths (e.g., fluent in addition, subtraction, and division) for *all* students in primary schools according to the Department of Education in the United Kingdom in 2022. Also, as mentioned in the knowledge of motor skills section, teachers may incorporate motor skills as daily living skills in autistic children (Lindsay, 2007; Travers et al., 2017). In this case, among teachers, motor skills may be perceived to have more importance in the school setting than academic achievement.

The current study also found that teachers' beliefs were positively correlated with their knowledge of motor skills. Although in the hierarchical regression analysis, teachers' beliefs and knowledge of motor skills are not predictors of each other, the correlation between belief and knowledge had an influence on each other. Blömeke et al. (2014) indicated that teachers' beliefs are a crucial aspect of teachers' perceptions of teaching situations and further influence the knowledge they choose to draw from in class, and their choice of teaching methods. It indicated that teachers who place more importance on motor skills tend to have more knowledge of motor skills and are more likely to choose teaching motor skills to the students. This finding highlights the need to conduct workshops to increase teacher beliefs to further influence their knowledge and choice of conducting motor skills activities in schools. Also, our findings indicate that school type was a predictor for teachers' frequency of activities of motor skills. Teachers from SEN schools placed a greater importance on motor skills than those from mainstream school. This finding aligns with Lindsay (2007) that SEN school teachers tend to focus more on different skills (e.g., daily living skills; social skills) development and physical activities for autistic children. Moreover, more than 70% of autistic children received their education in mainstream schools across the UK (Department of Education, 2022). In this case, teachers from mainstream schools may need more motor skills training workshops than those from SEN schools.

Strengths and Limitations

A key strength of the current study is that it provides the first newly developed and psychometrically robust tool to assess teachers' beliefs, knowledge and frequency of activities of motor skills in autistic children aged 7 to 11 years in mainstream and special education needs (SEN) schools in the United Kingdom – extending the existing literature that was lacking a consistent assessment tool. The survey was designed with

experts in the motor field, along with both mainstream and SEN teachers' co-production, to ensure the examples and the theories of the survey items were up to date and answered the research questions at hand. It draws on 114 teachers from a range of backgrounds, including job roles, years of teaching experience, and educational levels.

This study was not without its limitations, however. One limitation was the small sample size. The sample size calculator by *Qualtrics (www.qualtrics.com)* suggested that the survey required 385 participants, although sample sizes of previous studies (e.g., Callea et al., 2008; Van Rossum et al., 2019 & 2021) that examined teachers' understanding ranged from approximately 40 and 110. Therefore, the current sample in the present study was more than a hundred to allow for variation in completion rates. However, further research examining how representative the current study findings are for the entire school workforce, by looking at sub-groups (e.g., different culture; different job roles), is required. The current study relied on teacher self-report, which may result in low reliability and validity (Rosenman et al., 2011). However, EFAs/CFAs conducted would suggest there is good reliability and validity between the survey items. Future research should triangulate observational findings of teachers in practice to see whether this corresponds with their self-reported practices.

Implication

The current findings suggest that motor skills-related training for teachers, especially in mainstream schools, is needed. McMullen (1997) suggested that best practice and conductive beliefs are shaped via experience and formal training. As teachers' beliefs are a predictor for their knowledge, it is encouraged that more motor

skills-related resources (e.g., talks, workshops and activities) are shared in schools to increase teachers' beliefs and further influence their knowledge and implementation of activities.

Interestingly, our findings suggested that even though teachers have more beliefs of motor skills than academic skills, such as maths, teacher's responses to knowledge of motor skills were inconsistent. Previous literature (e.g., Eddy et al., 2021; Van Rossum et al., 2019) formulates the knowledge of motor skills survey items based on general motor skills knowledge, such as gross motor and fine motor. The current survey included general motor skills knowledge and underlying motor mechanisms knowledge. Teachers' responses towards underlying motor mechanisms were consistent. This finding is also supported by Wilson et al. (2018)'s systematic review, which found that standardised motor measures (e.g., Peabody Developmental Motor Scale; Movement Assessment Battery for Children) only give detail on global motor processing in autistic children and are scored using 0 or 1, which does not give enough detail of septicity of the underlying motor mechanisms (e.g., reaction time and kinematic analysis). Thus, further research could consider offering motor specificity training to teachers to enhance their knowledge and inform their beliefs and implementation practices, especially for mainstream schoolteachers. It will also be beneficial for other researchers to consider how the currently investigated factors may also impact on children's learning outcomes (e.g., their motor, literacy, and maths performance). Connecting these factors with children's learning in the school environment (Costa et al., 2021) will help target effective motor skills-related practices to autistic children.

Conclusion

This newly developed 72-item teacher-reported survey on teachers' beliefs, knowledge and frequency of activities of motor skills in autistic children aged 7 to 11 years old can help identify the teacher's level of understanding in motor skills development for autistic children and areas where they need extra support and training. More studies are still needed to replicate the survey in different populations of teachers from different countries or regions (e.g., Europe), as well as age groups and job roles. These findings may have implications for policy and practice, specifically the SEN Code of Practice and national curriculum, to include more teacher provision on beliefs of motor skills.

Chapter 7. General Discussion

The aim of the PhD program was to explore sensorimotor behaviours in autism. Four studies with different methodologies and aims were conducted to explore aspects of sensorimotor behaviours in autism. As illustrated in Table 17, the first study was a systematic review that examined whether sensorimotor control and learning processes differentiated autistic individuals from non-autistic individuals using movement outcomes, motor control outcomes, and kinematic analyses. The second study, a cross-sectional study, investigated whether VMI was a predictor of literacy skills in autistic children aged 7 to 11 years. The third study was an experimental study and had dual objectives: 1) to determine whether there were sensorimotor control differences in autistic compared to non-autistic children aged 7 to 11 years old; 2) to explore whether VMI control markers were predictors of literacy in children aged 7 to 11 years old. The fourth study was a survey to explore teachers' beliefs, knowledge, and frequency of activities related to motor skills, compared to literacy and math skills in autistic children aged 7 to 11 years.

Additionally, the key findings of each study are described in Table 1, and they are interconnected. The systematic review (Study 1) synthesised and evaluated movement outcomes, production measures, and kinematic markers, providing a theoretical basis and exploring measures for sensorimotor control processes in autistic individuals, which were further examined in Study 3. The experimental study was built on the theoretical foundations of Study 1 by exploring the underlying sensorimotor mechanisms in autistic compared to non-autistic children aged 7 to 11 years old. Extending the cross-sectional study (Study 2), Study 3 investigated whether

sensorimotor control markers (%TTPV) predicted literacy skills in children aged 7 to 11 years, following the methodological framework of Study 2. Finally, the survey (Study 4) investigated the teachers' understanding and application of motor skills in the school setting, compared to other key skills (i.e., literacy and maths skills). The discussion chapter is organised into 3 sections 1) Sensorimotor Behaviours Across Life Span; 2) Sensorimotor Behaviours and Literacy Skills; 3) Sensorimotor Behaviours in Education to appraise the key findings from the four studies and to outline limitations, implications, and conclusions.

Table 1. Overview of the Aims and Key Findings

Study 1: Systematic Review	Study 2: Cross-sectional Study	Study 3: Experimental Study	Study 4: Survey
Aim:	**Aim:**	**Aim:**	**Aim:**
To examine sensorimotor practice protocols on motor control and learning in autistic individuals, using sensorimotor outcomes and production measures, and kinematic analysis.	To examine whether VMI is a predictor of literacy skills in autistic children aged 7 to 11 years old	To examine 1) whether there were sensorimotor control differences in autistic compared to nonautistic children aged 7 to 11 years old; 2) whether VMI control markers were predictors of literacy in children aged 7 to 11 years old	To understand the beliefs, knowledge and frequency of activities of motor skills in teachers who worked with autistic children aged 7 to 11 years old, compared to literacy and maths skills.
Key Findings	**Key Findings**	**Key Findings**	**Key Findings**
Reaction time was the most frequent measure for sensorimotor control.	VMI was significantly correlated with reading (r = .51) and handwriting fluency (r = .53).	Autistic children had less error (SPE), more error variability, greater and more variability on percentage time to peak velocity (TTPV) than non-autistic children.	Teachers reported varying degrees of knowledge in motor skills.
Total movement time was the most frequent measure for sensorimotor learning.	FSIQ (β = .56) was the only predictor for reading (i.e., word reading and reading comprehension).	Task differences (copy vs trace) were found in most VMI planning and performance variables.	Teachers had stronger beliefs on statements of motor skills than in maths skills.

Over 50% of studies found sensorimotor control differences.	Age (β = .32) and reading (β = .44) were predictors for handwriting fluency.	SPE (r = .26) and TTPV (r = -.26) were significantly correlated with reading; TTPV was significantly correlated with handwriting fluency (r = -.35)	Belief and knowledge of motor skills were significantly correlated (r = .23).
Over 40% of studies found sensorimotor learning differences.		FSIQ (β = .43) and group (β = .38) were the predictors for reading.	Beliefs of maths (β = .75) and literacy skills (β = .16), and frequency of activities (β = .16) in motor were predictors for beliefs in motor skills.
Heterogeneity was found in terms of task type, number of trials and motor activities.		Age (β = .30) was the only predictor handwriting fluency	Living area (β = .19) was the only predictor for knowledge in motor skills.
			School type (β = 0.18), frequency of activities of maths (β = 0.41), and literacy (β = 0.41), knowledge of maths skills (β = 0.22) were predictors for frequency of activities in motor skills.

Sensorimotor Behaviours across Life Span

Most of the studies published in the autism literature have focused on research questions centered on investigating the two main diagnosis criteria (i.e., social interaction and repetitive behaviour) of autism (Leekam et al., 2011; Lord & Bishop, 2015; Smith et al., 2015). Whilst this makes sense, it is important to note that in the early writings of Leo Kanner (Kanner, 1943), research has acknowledged that the sensorimotor system shows differences in motor skills among autistic individuals... such as “clumsy” gait and gross motor performance difficulties. Sensorimotor differences received more attention in the 1990s via imitation studies (e.g., Loveland et al., 1994; Smith & Bryson, 1998; Stone et al., 1997) where the imitation problem in autism, which revealed problems with the representation of actions, was underpinned by sensorimotor processing differences rather than social processes. Even though sensorimotor processing differences are still not a core feature in the DSM-V diagnosis criteria of autism, it is now suggested that sensorimotor control differences are present in a high proportion (~87% of individuals) of the autistic population (e.g., Bhat et al, 2020; Licari et al., 2020; Miller et al., 2021). The pervasive aspect of sensorimotor processes is also reflected in the increasing interest and investigation in this area of autism as the findings from Study 1 (systematic review of papers from 1990 to 2021) showed only 1 study was conducted in the 1990s, whereas the number of sensorimotor studies increased across the following decades (i.e., 2000 – 2009: n = 11; 2010 – 2019: n = 72; 2020 – 2021: n = 13).

Given that sensorimotor control differences are present in ~87% of autistic individuals, the novelty of Study 1 was to focus the review specifically in terms of the underlying motor mechanisms (see also Miller et al., 2024), as opposed other

systematic reviews (Gandotra et al., 2020; Ruggeri et al., 2020; Sortwell et al., 2022) that have looked at movement (physical activity; motor competency; learning) based on studies that used standardised assessments to measure motor processes. By investigating the underlying motor mechanisms via motor control measures (e.g., reaction time; kinematic analysis; peak velocity) in Study 1, it was found that autistic individuals typically showed slower and more variable sensorimotor control processes compared to non-autistic individuals across lifespan (e.g., Foster et al., 2020a; Glazebrook et al., 2009; Rinehart et al., 2001). The findings of Study 1 also demonstrated that these sensorimotor control differences were persistent from early years to school-age, and adulthood (e.g., Crippa et al., 2021; Foster et al., 2023) in various tasks, such as gait (e.g., Rinehart et al., 2006c; Weiss et al., 2013;), upper limb movements (e.g., Hayes et al., 2016; Wild et al., 2012) and imitation (e.g., Buard et al., 2018; Gauthier et al., 2018; Xavier et al., 2018). Given that the overarching theme in the thesis was motor skills in autistic school children, it is noteworthy that the early detection of sensorimotor differences in autism can be traced back to infancy. For example, the findings from a recent systematic review (Lim et al., 2021) suggested that infants who were later diagnosed with autism exhibited early fine, gross, and generalised motor function difficulties as early as 6 months. It was also suggested that infants who were later diagnosed as autistic had poorer motor function than non-autistic children. These findings emphasize the importance of early detection and intervention for motor challenges in autistic individuals and the need to improve access to support and accommodations throughout their lives (Landa et al., 2022).

As aforementioned, sensorimotor control differences are prevalent in school age autistic children, compared to non-autistic children (e.g., Cavallo et al., 2021; Conson et al., 2013; Kostrubiec et al., 2018). Study 3 further investigated sensorimotor

control differences with visuomotor integration tasks (i.e., copying and tracing) in autistic children, compared to non-autistic children aged 7 to 11 years old (Key Stage 2). Based on the narrative synthesis findings of study 1, peak velocity and percentage time to peak velocity, a kinematic marker reflecting the sensorimotor planning, were used to quantify the sensorimotor control processes in study 3. The findings of Study 3 indicated that autistic children reached peak velocity later in their movements (i.e., a greater percentage of time to peak velocity) and exhibited more variability in the percentage of time to peak velocity compared to non-autistic children. It aligns with previous studies (Foster et al., 2020b, 2023; Gowen et al., 2020; Hayes et al., 2016; Vabalas et al., 2020), that demonstrate sensorimotor control differences between autistic and non-autistic individuals, using kinematic analysis. Importantly, percentage time to peak velocity is a sensorimotor planning marker, suggesting that autistic children were less efficient and had more variability during the sensorimotor planning processes (Fears et al., 2023; Glazebrook et al., 2006, 2009; Zheng et al., 2019), which could be driven by differences in visuomotor integration (Fears et al., 2023). These differences could have underpinned and affected other key domains in school-aged autistic children, such as daily living skills and school attainment activities. For example, in activities in daily living skills, such as using knives and forks, autistic children may expend additional energy that leads to a higher-level exertion and fatigue than non-autistic children when complete the same task (Fears et al., 2023). The high-level of exertion and fatigue would discourage autistic children's confidence in performing similar activities (Grenier, 2013) are present in many domains in school-aged autistic children, including physical activities, daily living skills and academic attainment activities, such as handwriting (Hellickx et al., 2013; Rossenblum et al., 2016). As in school attainment skills such as handwriting, autistic children exhibit less

effective integration to utilise visual information and motor functioning (Li-Tsang et al., 2018; Rossenblum et al., 2003), resulting them slower less handwriting fluency and further influence their academic progress (Fuentes et al., 2009), social and communicative development (Feder & Majnemer, 2007) and confidence in learning new skills (Hwang, 2010). These findings emphasize the importance of recognising sensorimotor challenges and developing motor-based intervention in school-aged autistic children, to improve their academic learning and skills development (Lee et al., 2022).

It is important to know that learning is a contentious topic in autism (Dawson et al., 2008). In the early writings of Kanner (1943), autistic individuals' learning patterns were "unusual" during the skill development. The ability of learning in autism was "non-existent" in the typical day-to-day environment (Lovaas & Smith, 2003), and "fundamentally impaired" (Klingner et al., 2006). Autistic learning pattern is also described as distinctive (Volkmar et al., 2004) and "subhuman" (Tomasello et al., 2005). Therefore, it is crucial to examine various aspects of autistic learning to attain a comprehensive understanding and to conscientiously consider the terminology employed in discussions about learning. The ability to learn novel movements is key to autism development as it influences the participation and competence in daily living activities, such as using a pencil or pen, cross a road, and zip clothes (Fears et al., 2022; Jasmin et al., 2009). Study 1 gained an up-to-date understanding of the sensorimotor learning processes in autistic, compared to non-autistic individuals. The results suggested that increased motor performance and less variability was found in post-test compared to pre-test in autism in different tasks, including upper limb movement (Foster et al., 2020a, 2020b, 2023; Hayes et al., 2016, 2018), imitation

(Taheri-Torbat et al., 2017), force production (Zhang et al., 2018), gait (Bonjanek et al., 2020). Although autistic children exhibited more total error, longer reaction time and more variability than non-autistic children at post-test, (e.g., Crippa et al., 2013; Fulceri et al., 2018; Nazarali et al., 2009), similar improvement in performance was found between both groups (Foster et al., 2020b, 2023; Glazebrook et al., 2009). These findings suggested that autistic individuals were capable to recruit and integrate the vision and motor information, generate internal model representations (even for novel movement, Foster et al., 2023), and further control the movement production (Foster et al., 2020b, 2023; Hayes et al., 2014, 2016). That is, the visuomotor integration processes during observational practice in autism was intact, that the action-observation processing was not a global deficit in autism (Williams et al., 2001, 2004a). Foster et al (2020b) also showed that autistic individuals' learning effect remained after a period of time (retention task). Study 1 further investigated the optimal practice protocol in autistic sensorimotor learning.

Although few studies have investigated practice types in sensorimotor learning in autism, Study 1 indicated that blocked-practice trial order (Shea & Morgan, 1979) could potentially be the optimal practice type (Foster et al., 2020b, 2023). With repeated trials, the action-plan is constantly updated through the comparison of efferent and reafferent sensorimotor information in the underlying sensorimotor control processes (Buccino et al., 2004; Carroll & Bandura, 1990). Taken together, autistic individuals are capable to develop sensorimotor learn, as they demonstrate similar improvement on performance as non-autistic individuals. Additionally, blocked-practice order tends to optimise autistic individuals' sensorimotor learning processes, compared to other practice types. Few studies investigate retention test and practice protocol in sensorimotor learning processes in autism. Therefore, further studies

should be targeted to examine the retention (longer term effect) and optimal practice type in autistic sensorimotor learning processes, to attain a comprehensive understanding in autism.

Sensorimotor Behaviours and Literacy Skills

Sensorimotor skills have been found to have associations with many domains, including physical activities, daily living skills and school attainment (Miller et al., 2024). Specifically, visuomotor integration (VMI) skills, that is the ability to integrate visual information and motor functioning (Beery & Beery, 2006), supports many activities that links to school attainment, such as fine motor skills used in handwriting (Longcamp et al., 2016; Rossenblum., 2016). Another key skill to develop in key stage 2 is reading comprehension, and VMI was found to be positively correlated with word reading and reading comprehension (Santi et al., 2015). Measures of VMI (e.g., Beery VMI) are often used as indicators of school readiness (Sulik, 2018).

The current study 2 and 3 with autistic children found a positive correlation relationship between VMI and both literacy skills (i.e., reading and handwriting), as per non-autistic children (Cameron et al., 2012, 2015; Carlson et al., 2013; Hopkins et al., 2019; Longcamp et al., 2016; Volman et al., 2006) across different age groups. VMI in early years non-autistic children were found to have significant positive association with emergent literacy (Becker et al., 2014; Bellochi et al., 2017; Cameron et al., 2012, 2015). Emergent literacy refers to the understanding that young children's acquisition of literacy is most effectively understood as a developmental continuum (Whitehurst & Lonigan, 1998). It encompasses several domains of reading and writing in early years, such as language and knowledge of letters, phonological awareness, and emergent

writing (Whitehurst & Lonigan, 1998), that predicted later literacy and language development (Roberts et al., 2005). VMI, along with executive function (EF), were found as predictors of improvement in phonological awareness in non-autistic children aged 5 years old (Cameron et al., 2012). The significant relationship between VMI and literacy skills were also found in school aged non-autistic children (Carlson et al., 2013; Hopskin et al., 2017). This suggested that VMI's positive impact on various literacy skills was persistent from early years, indicating that VMI and literacy skills would underpin similar cognitive processes (Cameron et al., 2012; Pagani et al., 2010). Therefore, it is important to consider VMI-related interventions to both early years and school-age children to increase their literacy skills.

In the current study 2 and 3, it was found that VMI was not a predictor of both reading and writing in both autistic and non-autistic children aged 7 to 11 years old. Full-scale IQ was found to be the strongest and only predictor of reading, aligned with some previous studies in non-autistic children (Christopher et al., 2012; Cutting & Scarborough, 2006; Mayes et al., 2007). Although VMI was highly associated with and/or predictor of reading in early years of literacy skills (Cameron et al., 2015; Kim et al., 2018), VMI might not be the strongest or the effect of VMI could was accounted by other variables such as IQ and EF (Khatib et al., 2022). Children in their early years reading tasks are generally involved in decoding the word (i.e., recognize the letter/word and ability to sound it out). Whereas more complex cognitive processes were incorporated in reading tasks, such as comprehending the word/sentence and having the capacity to articulate it through writing and verbally (Carlson et al., 2013). A similar process might explain that VMI was a close but not a significant predictor of handwriting in study 2 and 3. VMI might contribute more to early writing achievement

by facilitating learning how to write single letters to facilitate phonological awareness and early reading abilities (Khatib et al., 2022). In findings of study 2, reading was a predictor of handwriting, suggesting that the cognitive process in reading facilitates the transition of handwriting in autistic children aged 7 to 11 years old. This could be that retrieval of letter-sound and word-sound connections becomes more fluent in older age, the benefits of VMI faded in handwriting (Khatib et al., 2022).

A novelty of the study 3 is that VMI planning and performance marker (i.e., error and percentage time to peak velocity) was added into the hierarchical regression model to examine the predicting effect of the markers reflecting the underlying motor mechanisms. Although these markers were not found as predictors for both reading and writing in children aged 7 to 11 years old, significant linear relationships were found between percentage time to peak velocity and both literacy skills, and error and reading. Children who had a shorter percentage of time to reach peak velocity (i.e., when peak velocity occurs earlier in movement) showed better reading and writing outcomes. Percentage time to peak velocity is a key marker to identify the fidelity of biological motion imitation (Foster et al., 2020b), that reflects the sensorimotor planning processes. This indicated that the kinematic markers reflecting the underlying motor mechanisms, may also connect and reflect the domain general sensorimotor process for reading and writing. As aforementioned, children from early years would use VMI skills more to facilitate their reading and writing skills. It would be of interest to investigate whether the VMI planning, and performance markers could be predictors for children from early years' reading and writing skills.

Sensorimotor Behaviours in Education

School is a key environment for children to develop their skills, including school attainment, daily living skills and communication skills (Pellerigo & Hilton, 2012). According to the National Autistic Society report in 2021, over 160,000 autistic children are in schools across England. Over 70% of them are in mainstream, and the rest are in special needs education (SEN) schools. Pellicano et al. (2014) mentioned that most of the autistic students requires better support to engage and achieve in the school settings. In study 4, both mainstream and SEN school teachers were included. Mainstream teachers are required to make 'reasonable adjustments' to facilitate the learning and inclusion of children with special educational needs (SEN) in school (Greenstein, 2016). Besides having specialized knowledge about autism, teachers are also required to apply effective and suitable teaching methods (Frederickson et al., 2010; Odom et al., 2015), modify the curriculum, and provide the necessary support and resources (Lindsay et al., 2014).

As limited studies were on teachers' perceptions on motor skills (Eddy et al., 2021; Van Rossum et al., 2018) and they focus on the general motor skills difficulties (e.g., gross and fine motor skills), the current survey (study 4) is novel to investigate knowledge of underlying motor mechanisms in teachers. Teachers had less consistency in answering knowledge in motor skills (including questions about underlying motor mechanisms), that is when teachers didn't know or did not have sufficient motor skills training or knowledge in autistic children. Whereas teachers had more consistent answers in knowledge related to literacy and maths skills in key stage 2. This suggested that motor skills are not like literacy and maths skills that are shown with clear guidelines, requirements and teaching goals in national curriculum (DfE,

2013). Physical activities, that represent motor skills in national curriculum, only consist of 2 pages for key stage 1 and 2. Teachers may learn about children's age-specific motor differences and/or difficulties through their observations (O'Leary, 2020) or their personal interest. Only 22% of teachers received any form of motor skills training in our sample size, which is consistent with Maher & Fitzgerald (2020) that SEN school teachers lack appropriate motor skills-related training. Considering the importance of motor skills in autism underpinning various domains including daily living skills, school attainment and social development, it is critical to have workshops or trainings to increase motor skills knowledge to teachers in the school setting.

Teachers' beliefs were positively correlated with their knowledge of motor skills even though teachers' beliefs and knowledge of motor skills were not predictors of each other. Blömeke et al. (2014) indicated that teachers' beliefs may result in the knowledge they choose to draw from in class, and their choice of teaching methods. If teachers have placed more importance in motor skills, they tend to have more knowledge and further informed their teaching methods to autistic children within the school setting. Additionally, school type was found as a significant predictor for teachers' frequency of activities in motor skills. This finding is supported by Linsay (2007) that SEN teachers focus more on developing various domains of skills, such as daily living and social skills. That is different from mainstream teachers, as in SEN schools, "adaptive" national curriculum is applied based on autistic children's individual's needs. Also, the higher frequency in engaging motor skills activities may results in more opportunities to observe children's motor skills development (O'Leary, 2020). Although no school type differences were found in the knowledge of motor skills, SEN teachers may have more exposure (i.e., more autistic children within the school)

and more flexible teaching methods (i.e., “adaptive” national curriculum) than mainstream schoolteachers (Lindsay, 2007).

Impact on Theory and Practice

Autistic individuals show sensorimotor control and learning differences than non-autistic children across life span (e.g., Foster 2020a,2020b, 2023; Hayes et al., 2016), as well as in various domains such as daily living skills and school attainment (Khatib et al., 2020; Licari et al., 2020). Challenges in sensorimotor control and learnings are pervasive in autistic individuals, yet motor-related inventions are not easily assessed or prioritised (Bhat, 2020; Miller et al., 2024). This study expands the investigation of sensorimotor control differences in autistic and non-autistic children aged 7 to 11 years old. The findings increased the theoretical understanding of sensorimotor control processes in autism by using sensory planning and performance markers, using Gowen & Hamilton (2013)’s computational framework of motor control and Elliot et al. (2010)’s theoretical framework of motor control. The current study also shed light on the underlying motor mechanisms of motor control and learning processes in autism, building beyond the literature use standardised assessment to quantify motor competence.

In terms of practice implication of the current PhD, specifically, the relationship between VMI (e.g., a sensorimotor skill that utilise visual information and motor functioning) were found to be closely linked to school attainment skills, such as literacy skills since early years (e.g., Cameron et al., 2012, 2013; Kim et al., 2018). In the current PhD programme of work, the studies further explored not only the linear relationship of VMI in literacy skills (Cameron et al., 2015; Grissmer et al., 2010; Kim et al., 2018), but also explore whether VMI is a predictor and to what extent it

accounted for literacy skills. In both autistic and non-autistic children aged 7 to 11 years old, VMI is not a predictor for either reading or handwriting. However, VMI had moderate to strong correlation with both literacy skills in both autistic and non-autistic individuals. More importantly, as a novelty in the current PhD programme of work, sensorimotor planning and performance marker, reflecting the underlying motor mechanisms, were examined on its relationship and whether they were predictors of literacy skills. Although both are not predictors, the planning and performance markers had positive associations with both literacy skills. This suggests that the underlying motor mechanisms, which is related to the domain general sensorimotor processes, as well as other processes such as joint attention and intention when doing the motor tasks (Bedford et al., 2016; Iverson et al., 2018), could underpin the similar domain general process as reading and writing. Further research is suggested to investigate the sensorimotor planning and performance markers, on literacy outcomes, especially for young autistic children.

Teachers' beliefs, knowledge and frequency of activities are important as they influence the teaching methods and guidance of skills development in the school setting, especially when working with SEN children (Lindsay et al., 2014) The current findings including both mainstream and SEN teachers, suggested that there was lack of knowledge of motor skills in all teachers. Despite motor skills differences and/or difficulties were prevalence across life span and can be observed as early as 6 months (Lim et al., 2021), all teachers gain more knowledge in key school attainment skills such as literacy and maths skills. It is also shown in the findings that SEN teachers had more frequency of activities of motor skills in the school setting. However, over 70 % of autistic children are in mainstream schools. This suggested an important need

to offer motor-related workshops and trainings to mainstream schoolteachers to be more effectively working with autistic children.

Limitations and Future Directions

While the current PhD body of work provided insights into sensorimotor control processes, and literacy skills in autistic children aged 7 to 11 years old, as well as teachers' current perspectives and activities in the school setting. It is important to recognize the limitations in these studies to inform better practices. In study 2 and 3, although larger number of participants were recruited [i.e., study 2 (verbal children: *n* = 51); study 3 (autistic children: n = 32; non-autistic children: n = 29)], the general rule of thumb for hierarchical regression analysis is *n* = 50 (Wilson et al., 2007). This results in the fact that for study 3, no separate regression analysis was carried out to examine the predictors of literacy skills in autistic and non-autistic children independently, as in other studies using the similar methodology (Dockrell et al., 2014; Hellickx et al., 2013). It is important to acknowledge that a follow-up study with a larger sample sized should be carried out (Kadam & Bhalerao, 2010).

In study 3, two VMI planning and performance markers (i.e., error and percentage time to peak velocity) were carried out to examine the relationship of these markers and the potential predicting effect to literacy in children aged 7 to 11 years old. As shown in the systematic review, over 10 movement outcomes and production measures were synthesised across different age groups in different tasks. More planning and performance markers could also be analysed in the regression analysis. Nonetheless, exceeding independent variables to enter in the regression analysis could result in invalidity in the findings of the analysis. The two markers (error and

percentage time to peak velocity) were chosen as 1) error was shown as a frequent marker showing the motor performance in the literature; 2) percentage time to peak velocity as a kinematic marker showing the motor planning processes. Both markers were used in the mean differences test (ANOVA) and found group differences. In future studies, larger sample size and more measures of sensorimotor planning and performances should be investigated in terms of its relationship and predicting effect to literacy.

Although no significant predicting effect of VMI planning and performance markers in literacy in autistic children aged 7 to 11 years old, the correlation analysis still show the statistically significant relationship between VMI planning and performance marker and literacy skills. As many studies have shown VMI, using standardized assessments, is a predictor to literacy skills at early years (Cameron et al., 2012; 2015; Kim et al., 2018), the next step would be to investigate whether the VMI planning and performance, reflecting the underlying motor mechanisms, would be a predictor for literacy skills at early years (e.g., emergent literacy skills). As motor differences and/or difficulties in autism across life span and in various domains (e.g., school attainment), more motor-related interventions and practice should be assessed and prioritized. Meanwhile, teachers, particularly mainstream schoolteachers, should receive more motor-related workshops and training to further inform their teaching methods in motor skills in autistic children they work with.

Conclusion

This PhD programme of work focused on 1) sensorimotor behaviours across life span; 2) sensorimotor behaviours and literacy skills; 3) sensorimotor behaviours

in education. It was found through the systematic review that autistic individuals had sensorimotor control differences compared to non-autistic individuals across life span, suggesting that sensorimotor control differences in autism was prevalent. Moreover, study 3 was the first study investigating the relationship between VMI planning and performance markers and literacy skills, and whether they were predictors of literacy skills in autistic children aged 7 to 11 years old. Although they are not predictors, significant associations were found between MI planning and performance markers and literacy skills, suggesting that they may underpin similar cognitive processes in children aged 7 to 11 years old. Finally, a novel survey investigated teachers' beliefs, knowledge, and frequency of activities on motor skills, sharing further implications of motor-related training and workshops to be implemented in the school system.

Chapter 8: Reference

Abbott R. D., Berninger V. W., & Fayol M. (2010). Longitudinal relationships of levels of language in writing and between writing and reading in Grades 1 to 7. *Journal of Educational Psychology*, 102, 281–298.

Achen, C. (1982). *Interpreting and Using Regression*. Sage, Beverly Hills, CA.

Adolph, K. E., & Berger, S. E. (2005). Physical and Motor Development. In M. H. Bornstein & M. E. Lamb (Eds.), *Developmental Science: An Advanced Textbook* (pp. 223–281). Lawrence Erlbaum Associates Publishers.

Adolph, K. E., Cole, W. G., Komati, M., Garciaguirre, J. S., Badaly, D., Lingeman, J. M., Chan, G. L. Y., & Sotsky, R. B. (2012). How Do You Learn to Walk? Thousands of Steps and Dozens of Falls per Day. *Psychological Science*, 23(11), 1387-1394.

Alloway, T. P. (2007). Working memory, reading, and mathematical skills in children with developmental coordination disorder. *Journal of Experimental Child Psychology, 96,* 20–36.

Ament, K., Mejia, A., Buhlman, R., Erklin, S., Caffo, B., Mostofsky, S., & Wodka, E. (2015). Evidence for specificity of motor impairments in catching and balance in children with autism. *Journal of Autism and Developmental Disorders*, *45(3),* 742–751.

American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders* (4th ed.). American Psychiatric Publishing, Inc.

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders (DSM-5)*. Washington DC: American Psychiatric Pub

Anderson, D. I., Magill, R. A., & Sekiya, H. (2001). Motor learning as a function of KR schedule and characteristics of task-intrinsic feedback. *Journal of Motor Behaviour, 33(1),* 59–66.

Andrew, M. (2016). *Imitation of Atypical Biological Motion in Autism Spectrum Disorders* (Order No. 10595432). Available from ProQuest Dissertations & Theses Global. (1896110080). https://www.proquest.com/dissertations-theses/imitation-atypical-biological-motion-autism/docview/1896110080/se-2

Ardalan, A., Assadi, A. H., Surgent, O. J., & Travers, B. G. (2019). Whole-Body Movement during Videogame Play Distinguishes Youth with Autism from Youth with Typical Development. *Scientific Reports, 9(1),* 20094.

Armstrong, R.A. (2017). Recommendations for analysis of repeated measures designs: testing and correcting for sphericity and use of MANOVA and mixed model analysis. *Ophthalmic and Physiological Optics, 37*, 585–593.

Asperger H. (1944). Die Autistisehen Psychopathen im Kindesalter. *Archiv für Psychiatrie und Nervenkrankheiten 117:* 76–136.

Aspers, P., & Corte, U. (2019). What is Qualitative in Qualitative Research. *Qualitative Sociology,* 42(2), 139–160.

Baddeley, A. D., Hitch, G. J., & Allen, R. J. (2009). Working memory and binding in sentence recall. *Journal of Memory and Language, 61*(3), 438–456.

Baio, J., Wiggins, L., Christensen, D. L., Maenner, M. J., Daniels, J., Warren, Z., Kurzius-Spencer, M., Zahorodny, W., Robinson Rosenberg, C., White, T., Durkin, M. S., Imm, P., Nikolaou, L., Yeargin-Allsopp, M., Lee, L. C., Harrington, R., Lopez, M., Fitzgerald, R. T., Hewitt, A., Pettygrove, S., …& Dowling, N. F. (2018). Prevalence of Autism Spectrum Disorder Among Children Aged 8 Years - Autism and Developmental Disabilities Monitoring Network, 11 Sites, United States, 2014. *Morbidity and Mortality Weekly Report. Surveillance Summaries* (Washington, D.C.: 2002), 67(6), 1–23.

Baird, G., Charman, T., Baron-Cohen, S., Cox, A., Swettenham, J., Wheelwright, S., & Drew, A. (2000). A screening instrument for autism at 18 months of age: a 6-year follow-up study. *Journal of the American Academy of Child and Adolescent Psychiatry, 39(6),* 694–702.

Baker, L. (1996). Social influences on metacognitive development in reading. In C. Cornoldi & J. Oakhill (Eds.), *Reading Comprehension Difficulties: Processes and Interventions* (pp. 331–351). Hillsdale, NJ: Lawrence Erlbaum Associates.

Bandura, A. (1989). Human agency in social cognitive theory. *American Psychologist, 44*(9), 1175–1184.

Barnett, A., Henderson, S. E., Scheib, B., & Schulz, J. (2007). *The Detailed Assessment of Speed of Handwriting (DASH) [Assessment instrument].* Pearson.

Barnett-Page, E., & Thomas, J. (2009). Methods for the synthesis of qualitative research: A critical review. *BMC Medical Research Methodology, 9*, 59.

Barnett, L. M., van Beurden, E., Morgan, P. J., Brooks, L. O., & Beard, J. R. (2009). Childhood motor skill proficiency as a predictor of adolescent physical activity. *The Journal of Adolescent Health: Official Publication of the Society for Adolescent Medicine, 44(3),* 252–259.

Beaujean, A. A. (2013). Factor analysis using R. *Practical Assessment, Research & Evaluation*, *18(4),* 1–11.

Becchio, C., Pierno, A., Mari, M., Lusher, D., & Castiello, U. (2007). Motor contagion from gaze: The case of autism. *Brain*, *130*, 2401–2411.

Becker, D. R., Miao, A., Duncan, R., & McClelland, M. M. (2014). Behavioural self-regulation and executive function both predict visuomotor skills and early academic achievement. *Early Childhood Research Quarterly. 29*, 411-424.

Becker, E. S., Goetz, T., Morger, V., & Ranellucci, J. (2014). The Importance of Teachers' Emotions and Instructional Behaviour for Their Students' Emotions—An Experience Sampling Analysis. *Teaching and Teacher Education*, *43*, 15-26.

Bedford, R., Pickles, A., & Lord, C. (2016). Early gross motor skills predict the subsequent development of language in children with autism spectrum disorder. *Autism Research: Official Journal of the International Society for Autism Research*, *9*(*9),* 993–1001.

Beery, K.E. (1997). *The Beery-Buktenica VMI: Developmental Test of Visual-Motor Integration with Supplemental Developmental Tests of Visual Perception and Motor Coordination: Administration, Scoring, and Teaching Manual.* NJ: Modern Curriculum Press.

Beery K. E., Buktenica N. A., & Beery N. A. (2010). *The Beery–Buktenica Developmental Test of Visual–Motor Integration: Administration, Scoring, and Teaching Manual* (6th ed.). Minneapolis, MN: Pearson.

Beggs, W. D. A., & Howarth, C. I. (1972). The Movement of the Hand towards a Target. *Quarterly Journal of Experimental Psychology*, *24(4),* 448-453.

Bellocchi, S., Muneaux, M., Huau, A., Lévêque, Y., Jover, M., & Ducrot, S. (2017). Exploring the Link between Visual Perception, Visual-Motor Integration, and Reading in Normal Developing and Impaired Children using DTVP-2. *Dyslexia (Chichester, England), 23(3),* 296–315.

Berninger, V. W., Yates, C., Cartwright, A., Rutberg, J., Remy, E., & Abbott, R. (1992). Lower-level developmental skills in beginning writing. *Reading and Writing: An Interdisciplinary Journal*, *4*, 257-280.

Bewick, V., Cheek, L., & Ball, J. (2003). Statistics review 7: Correlation and regression. *Critical care (London, England)*, *7(6)*, 451–459.

Bhat, A. N. (2020). Is motor impairment in autism spectrum disorder distinct from developmental coordination disorder? A report from the SPARK study. *Physical Therapy, 100(4),* 633–644

Biffi, E., Costantini, C., Ceccarelli, S. B., Cesareo, A., Marzocchi, G. M., Nobile, M., Molteni, M., & Crippa, A. (2018). Gait Pattern and Motor Performance During Discrete Gait Perturbation in Children With Autism Spectrum Disorders. *Frontiers in psychology, 9*, 2530.

Bilton, C., & Tillotson, S. (2020). Improving literacy in KS1: Guidance report. *The Education Endowment Foundation.*

Bird, G., & Heyes, C. (2005). Effector-Dependent Learning by Observation of a Finger Movement Sequence. *Journal of Experimental Psychology: Human Perception and Performance, 31*(2), 262–275.

Bird, G., Leighton, J., Press, C., & Heyes, C. (2007). Intact automatic imitation of human and robot actions in autism spectrum disorders. Proceedings. *Biological Sciences*, *274(1628),* 3027–3031.

Blömeke, S., Hsieh, F.J., Kaiser, G., & Schmidt, W. (2014). International Perspectives on Teacher Knowledge, Beliefs and Opportunities to Learn. *TEDS-M Results*. Heidelberg: Springer Dordrecht.

Bojanek, E. K., Wang, Z., White, S. P., & Mosconi, M. W. (2020). Postural control processes during standing and step initiation in autism spectrum disorder. *Journal of Neurodevelopmental Disorders, 12(1),* 1.

Bormuth, J. R. (1973). Reading literacy: Its definition and assessment. *Reading Research Quarterly*, 7-66.

Bremer, E., Crozier, M., & Lloyd, M. (2016). A systematic review of the behavioural outcomes following exercise interventions for children and youth with autism spectrum disorder. *Autism: the International Journal of Research and Practice*, *20(8),* 899–915.

Brezis, R. S., Noy, L., Alony, T., Gotlieb, R., Cohen, R., Golland, Y., & Levit-Binnun, N. (2017). Patterns of Joint Improvisation in Adults with Autism Spectrum Disorder. *Frontiers in psychology, 8*, 1790.

Brian, J., Bryson, S.E., Garon, N., Roberts, W., Smith, I.M., Szatmari, P., & Zwaigenbaum, L. (2008). Clinical assessment of autism in high-risk 18-month-olds. *Autism, 12,* 433–456.

Brian J. A., Smith I. M., Zwaigenbaum L., & Bryson S. E. (2017). Cross-site randomized control trial of the Social ABCs caregiver-mediated intervention for toddlers with autism spectrum disorder. *Autism Research*, *10(10),* 1700–1711.

Brick, J. M., & Kalton, G. (1996). Handling missing data in survey research. *Statistical Methods in Medical Research*, *5(3),* 215–238.

Brickhouse, N.W. (1990). Teachers' beliefs about the nature of science and their relationship to classroom practice. *Journal of Teacher Education*, *41*, 53–62.

Brock L. L., Kim H., & Grissmer D. W. (2018). Longitudinal associations among executive function, visuomotor integration, and achievement in a high-risk sample. *Mind, Brain, and Education*, *12*, 23-27.

Brown, M. E., Trevino, L. K., & Harrison, D. A. (2005). Ethical leadership: A social learning perspective for construct development and testing. *Organizational Behaviour and Human Decision Processes, 97*, 117–134.

Brown, T. A. (2006). *Confirmatory Factor Analysis for Applied Research*. New York: The Guilford Press.

Brown, H. M., & Klein, P. D. (2011). Writing, Asperger syndrome and theory of mind. *Journal of Autism and Developmental Disorders, 41(11),* 1464–1474.

Bryson S., Zwaigenbaum L., McDermott C., Rombough V., & Brian J. (2008). The autism observation scale for infants: Scale development and reliability data. *Journal of Autism and Developmental Disorders*, *38*, 731–738.

Burd, L., Fisher, W., & Kerbeshan, J. (1987). A prevalence study of pervasive developmental disorders in North Dakota. J*ournal of the American Academy of Child and Adolescent Psychiatry, 26*, 700–703.

Byrne, R. W., & Russon, A. E. (1998). Learning by imitation: A hierarchical approach. *Behavioural and Brain Sciences, 21*(5), 667–721.

Buard, I., Kronberg, E., Steinmetz, S., Hepburn, S., & Rojas, D. C. (2018). Neuromagnetic Beta-Band Oscillations during Motor Imitation in Youth with Autism. *Autism research and treatment,* 9035793.

Buccino, G., Vogt, S., Ritzl, A., Fink, G.R., Zilles, K., Freund, H.J. & Rizzolatti, G. (2004). Neural circuits underlying imitation learning of hand actions: An event-related fMRI study. *Neuron 42(2):*323–34.

Bullock, D., Grossberg, S., & Guenther, F. H. (1993). A self-organizing neural model of motor equivalent reaching and tool use by a multijoint arm. *Journal of Cognitive Neuroscience*. *5*, 408–435.

Callea, M. B., Spittle, M., O'Meara, J., & Casey, M. (2008). Primary School Teacher Perceived Self-Efficacy to Teach Fundamental Motor Skills. *Research in Education, 79(1),* 67–75

Cameron, C., Brock, L.L., Murrah, W.M., Bell, L.H., Worzalla, S.L., Grissmer, D., & Morrison, F.J. (2012). Fine motor skills and executive function both contribute to kindergarten achievement. *Child Development, 83*, 1229–1244.

Cameron, C.E., Brock L.L., & Hatfield, B. (2013). Visuomotor skills compensate for poor inhibitory control in predicting preschool readiness. *In: Biennial Meeting of the Society for Research on Child Development*, Seattle, WA.

Cameron, C. E., Brock, L. L., Hatfield, B. E., Cottone, E. A., Rubinstein, E., LoCasale-Crouch, J., & Grissmer, D. W. (2015). Visuomotor integration and inhibitory control compensate for each other in school readiness. *Developmental Psychology, 51(11),* 1529–1543.

Cameron, C. E., Cottone, E. A., Murrah, W. M., & Grissmer, D. W. (2016). How are motor skills linked to children's school performance and academic achievement?

Child Development Perspectives, *10*, 93–98.

Carroll, W. R., & Bandura, A. (1982). The role of visual monitoring in observational learning of action patterns: making the unobservable observable. *Journal of Motor Behaviour*, *14(2),* 153–167.

Centelles, L., Assaiante, C., Etchegoyhen, K., Bouvard, M., & Schmitz, C. (2013). From action to interaction: exploring the contribution of body motion cues to social understanding in typical development and in autism spectrum disorders. *Journal of Autism and Developmental Disorders*, *43(5),* 1140–1150.

Caron MJ, Mottron L, Berthiaume C, Dawson M. (2006). Cognitive mechanisms, specificity and neural underpinnings of visuospatial peaks in autism. *Brain.* 129(Pt 7):1789-802

Carlson, A. G., Rowe, E., & Curby, T. W. (2013). Disentangling fine motor skills' relations to academic achievement: the relative contributions of visual-spatial integration and visual-motor coordination. *The Journal of Genetic Psychology*, *174(5-6),* 514–533.

Cavallo, A., Romeo, L., Ansuini, C., Battaglia, F., Nobili, L., Pontil, M., Panzeri, S., & Becchio, C. (2021). Identifying the signature of prospective motor control in children with autism. *Scientific Reports, 11(1),* 3165.

Charman, T., Young, G. S., Brian, J., Carter, A., Carver, L. J., Chawarska, K., Curtin, S., Dobkins, K., Elsabbagh, M., Georgiades, S., Hertz-Picciotto, I., Hutman, T., Iverson, J. M., Jones, E. J., Landa, R., Macari, S., Messinger, D. S., Nelson, C. A., Ozonoff, S., & Zwaigenbaum, L. (2017). Non-ASD outcomes at 36 months in siblings at familial risk for autism spectrum disorder (ASD): A baby siblings research consortium (BSRC) study. *Autism Research*, *10(1),* 169–178.

Chen, F.C., & Tsai, C.L. (2016). A light fingertip touch reduces postural sway in children with autism spectrum disorders. *Gait Posture*. *43*:137-40.

Chen, L. C., Su, W. C., Ho, T. L., Lu, L., Tsai, W. C., Chiu, Y. N., & Jeng, S. F. (2019). Postural Control and Interceptive Skills in Children With Autism Spectrum Disorder. *Physical Therapy, 99(9),* 1231–1241.

Chen, L. (2019). *A pilot study on the gait kinematics in children with autism during perturbations of visual scene and support surface.* Available from: The University of Texas Library. https://repositories.lib.utexas.edu/items/f2e2cd8b-3710-4b50-b655-e0bed7884bae

Chen, Y., Fei, X., Wu, T., Li, H., Xiong, N., Shen, R., Wang, Y., Liang, A., & Wang, H. (2022). The relationship between motor development and social adaptability in autism spectrum disorder. *Frontiers in Psychiatry, 13*, 1044848.

Cheung, R. H. P. (2012). Teaching for Creativity: Examining the Beliefs of Early Childhood Teachers and Their Influence on Teaching Practices. *Australasian Journal of Early Childhood, 37 (3)*: 43–51.

Chiu, Y. D. (2018). The Simple View of Reading Across Development: Prediction of Grade 3 Reading Comprehension from Prekindergarten Skills. *Remedial and Special Education*, *39(5),* 289-303.

Choi, B., Leech, K. A., Tager-Flusberg, H., & Nelson, C. A. (2018). Development of fine motor skills is associated with expressive language outcomes in infants at high and low risk for autism spectrum disorder. *Journal of Neurodevelopmental Disorders*, *10(14),* 1–11.

Christopher, M. E., Miyake, A., Keenan, J. M., Pennington, B., DeFries, J. C., Wadsworth, S. J., Willcutt, E., & Olson, R. K. (2012). Predicting word reading and comprehension with executive function and speed measures across development: a latent variable analysis. Journal of experimental psychology. General, 141(3), 470–488.

Clearfield, M.W. (2011). Learning to walk changes infants' social interactions. *Infant Behaviour and Development*, 34, 15–25.

Cleaver, K., Essex, R., & Malamateniou, C. (2021). A systematic scoping review and textual narrative synthesis of undergraduate paediatric nursing simulations: what, why, and how? *Clinical Simulation In Nursing*; *53*:10–31.

Coleman, B., & Dyment, J. E. (2013). Factors that limit and enable preschool-aged children's physical activity on child care centre playgrounds. *Journal of Early Childhood Research*, *11(3),* 203–221.

Coll, S.-M., Foster, N. E. V., Meilleur, A., Brambati, S. M., & Hyde, K. L. (2020). Sensorimotor skills in autism spectrum disorder: A meta-analysis. *Research in Autism Spectrum Disorders*, *76,* 1010570.

Colombo-Dougovito, A.M., & Block, M.E. (2019). Fundamental Motor Skill Interventions for Children and Adolescents on the Autism Spectrum: a Literature Review. *Review Journal of Autism and Developmetal Disorders 6*, 159–171.

Cook, J. L., Blakemore, S. J., & Press, C. (2013). Atypical basic movement kinematics in autism spectrum conditions. *Brain, 136(9),* 2816-2824.

Cook, J., Swapp, D., Pan, X., Bianchi-Berthouze, N., & Blakemore, S. J. (2014). Atypical interference effect of action observation in autism spectrum conditions. *Psychological Medicine, 44(4),* 731–740.

Cook, J. (2016). From movement kinematics to social cognition: the case of autism. Philosophical Transactions of the Royal Society of London. *Series B, Biological sciences, 371(1693),* 20150372.

Connor C. M., Lara J. J., Crowe E. C., & Meadows J. G. (2009). Instruction, student engagement, and reading skill growth in reading first classrooms. *Elementary School Journal*, *109*, 221–250.

Conson, M., Mazzarella, E., Frolli, A., Esposito, D., Marino, N., Trojano, L., Massagli, A., Gison, G., Aprea, N., & Grossi, D. (2013). Motor imagery in Asperger syndrome: testing action simulation by the hand laterality task. *PloS One, 8(7)*, e70734.

Constantino, J. N., & Gruber, C. (2012). *The Social Responsiveness Scale Manual, (SRS-2), 2nd Edition.* Los Angeles: CA: Western Psychological Services.

Copley, J. V. (2004). The early childhood collaborative: A professional development model to communicate and implement the standards, in D. H. Clements and J. Sarama (eds) *Engaging Young Children in Mathematics: Standards for Early Childhood Mathematics Education,* pp. 401–414. Mahwah, NJ: Lawrence Erlbaum Associates.

Conrad-Forrest, A., Todd, T., Mache, M., & Jarvis, D. (2020). Kinematic Analysis Of Single-leg Hopping In Adults With And Without Autism Spectrum Disorder: 1015 Board #141 May 27 1:30 PM - 3:00 PM. *Medicine & Science in Sports & Exercise 52(7S):*p 257.

Costa, H. M., Outhwaite, L. A., & Van Herwegen, J. (2021). Preschool teachers' training, beliefs and practices concerning mathematics in pre-schools in the UK: implication for education and practice. *Psyarxiv. Preprint.*

Costales, J., Catulay, J. J. J., Costales, J., & Bermudez, N. (2022). Kaiser-MeyerOlkin Factor Analysis: A Quantitative Approach on Mobile Gaming Addiction using Random Forest Classifier. *2022 the 6th International Conference on Information System and Data Mining*, 18–24.

Craig, P., Dieppe, P., Macintyre, S., Michie, S., Nazareth, I., Petticrew, M., & Medical Research Council Guidance (2008). Developing and evaluating complex interventions: the new Medical Research Council guidance. *BMJ (Clinical Research Edition.)*, 337, a1655.

Creswell, J.W. (2003). *Research Design: Qualitative, Quantitative and Mixed Methods Approaches (2nd ed.).* Thousand Oaks, CA: Sage.

Crippa, A., Forti, S., Perego, P., & Molteni, M. (2013). Eye-hand coordination in children with high functioning autism and Asperger's disorder using a gap-overlap paradigm. *Journal of Autism and Developmental Disorders, 43(4),* 841–850.

Crippa, A., Craig, F., & Busti-Ceccarelli, S. (2021). A multimethod approach to assessing motor skills in boys and girls with autism spectrum disorder. *Autism. 25(5):*1481-1491

Crossman, E. R., & Goodeve, P. J. (1983). Feedback control of hand-movement and Fitts' Law. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 35A (2*), 251–278.

Cutting, L. E., & Scarborough, H. S. (2006). Prediction of reading comprehension: Relative contributions of word recognition, language proficiency, and other cognitive skills can depend on how comprehension is measured. *Scientific Studies of Reading*, *10*, 277–299.

David, F.J., Baranek, G.T., Giuliani, C.A., Mercer, V.S., Poe, M.D., Thorpe, D.E. (2009). A pilot study: coordination of precision grip in children and adolescents with high functioning autism. *Pediatric Physical Therapy. 21(2*):205-11.

David, F. J., Baranek, G. T., Wiesen, C., Miao, A. F., & Thorpe, D. E. (2012). Coordination of precision grip in 2-6 years-old children with autism spectrum disorders compared to children developing typically and children with developmental disabilities. *Frontiers in Integrative Neuroscience, 6,* 122.

Davis J. L., & Matthews R. N. (2010). NEPSY-II review. *Journal of Psychoeducational Assessment*, *28(2),* 175–182.

Dawson, G. (2008). Early behavioural intervention, brain plasticity, and the prevention of autism spectrum disorder. *Development and psychopathology, 20(3),*775-803.

Denton, C.A., York, M.J., Francis, D.J., Haring, C., Ahmed, Y.,& Bidulescu, A. (2017). An investigation of an intervention to promote inference generation by adolescent poor comprehenders. *Learning Disabilities Research & Practice*, *32(2),* 85–98.

Denyer, D., & Tranfield, D. (2009). Producing a systematic review. In D. A. Buchanan, & A. Bryman (Eds.), *The Sage Handbook of Organizational Research Methods* (pp. 671–689). Sage Publications Ltd.

Department for Education. (2013). *The National Curriculum in England: Key Stages 1 and 2 Framework Document.* Available at: https://www.gov.uk/government/publications/national-curriculum-in-englandprimary-curriculum

Department for Education. (2022). *Special Educational Needs in England*. London: Department for Education.

Department for Education. (2024). *Special Educational Needs and Disability: An Analysis and Summary of Data Sources*. Department for Education.

De Waal, E., Pienaar, A.E. & Coetzee, D. (2018). Gender differences in academic achievement of children with developmental coordination disorder. *South African Journal of Childhood Education. 8(1):* 1–10.

Diaz, C. (2019). *Sensory Integration And Its Role In Behavioral Plasticity In Children Diagnosed With Autism Spectrum Disorder.* Available from University of Texas at El Paso ScholarWorks@UTEP, Open Access Theses & Dissertations. https://scholarworks.utep.edu/cgi/viewcontent.cgi?article=3956&context=open_etd

Dillon, S.R., Adams, D., Goudy, L., Bittner, M., & McNamara, S. (2016). Evaluating exercise as evidence-based practice for individuals with autism spectrum disorder. *Frontiers in Public Health*, *4*, 290.

Dockrell, J. E., Ricketts, J., Charman, T., & Lindsay, G. (2014). Exploring writing products in students with language impairments and autism spectrum disorder. *Learning and Instruction*, *32*, 81–90.

Downey, R., & Rapport, M. J. (2012). Motor activity in children with autism: a review of current literature. *Pediatric Physical Therapy: the Official Publication of the Section on Pediatrics of the American Physical Therapy Association*, *24(1),* 2–20.

Dufek, J. S., Eggleston, J. D., Harry, J. R., & Hickman, R. A. (2017). A Comparative Evaluation of Gait between Children with Autism and Typically Developing Matched Controls. *Medical Sciences (Basel, Switzerland), 5(1),* 1.

Duke, N.K., Ward, A.E., & Pearson, P.D. (2021). The Science of Reading Comprehension Instruction. *The Reading Teacher*, *74(6),* 663– 672.

Eggleston, J. D., Harry, J. R., Hickman, R. A., & Dufek, J. S. (2017). Analysis of gait symmetry during over-ground walking in children with autism spectrum disorder. *Gait & posture, 55,* 162–166.

Elliot, C., & Smith, P. (2011). *British Ability Scales—Third Edition (BAS-3)*. GL Assessment.

Elliott, D., Hansen, S., Grierson, L. E., Lyons, J., Bennett, S. J., & Hayes, S. J. (2010). Goal-directed aiming: Two components but multiple processes. *Psychological Bulletin, 136*, 1023–1044.

Elsabbagh, M., Divan, G., Koh, Y. J., Kim, Y. S., Kauchali, S., Marcín, C., Montiel-Nava, C., Patel, V., Paula, C. S., Wang, C., Yasamy, M. T., & Fombonne, E. (2012). Global prevalence of autism and other pervasive developmental disorders. Autism research: official journal of the International Society for Autism Research, 5(3), 160–179.

Ericsson, I., & Karlsson, M. K. (2014). Motor skills and school performance in children with daily physical education in school--a 9-year intervention study. *Scandinavian Journal of Medicine & Science in Sports, 24(2),* 273–278.

Ernest, P. (1989). The knowledge, beliefs, and attitudes of the mathematics teacher: A model. *Journal of Education for Teaching*, *15, 1,* 13-34.

Fabbri-Destro, M., Cattaneo, L., Boria, S., & Rizzolatti, G. (2009). Planning actions in autism. *Experimental Brain Research*, *192*, 521–525.

Farquhar, M., Preston, N., Evans, C. J., Grande, G., Short, V., Benalia, H., Higginson, I. J., Todd, C., & MOREcare (2013). Mixed methods research in the development and evaluation of complex interventions in palliative and end-of-life care: report on the MORECare consensus exercise. *Journal of Palliative Medicine, 16(12),* 1550–1560.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioural, and biomedical sciences. *Behaviour Research Methods*, *39(2),* 175–191.

Fears, N. E., Palmer, S. A., & Miller, H. L. (2022). Motor skills predict adaptive behaviour in autistic children and adolescents. *Autism Research. 15,* 1083–1089.

Feder. K., & Majnemer, A. (2007). Handwriting development, competency, and intervention. *Developmental Medicine & Child Neurology 49(4):* 312–317.

Fischer, U., Suggate, S. P., & Stoeger, H. (2020). The Implicit Contribution of Fine Motor Skills to Mathematical Insight in Early Childhood. *Frontiers in Psychology, 11,* 1143.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47*(6), 381–391

Fitts, P. M., & Peterson, J. R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology, 67*(2), 103–112.

Fletcher-Flinn, C., Elmes, H., & Stugnell, D. (1997). Visual–perceptual and phonological factors in the acquisition of literacy among children with congenital developmental coordination disorder. *Developmental Medicine and Child Neurology*, *39,* 158–166.

Fletcher-Watson, S., & Happé, F. (2019). *Autism: A New Introduction to Psychological Theory and Current Debate. Routledge.*

Fleury, A., Kushki, A., Tanel, N., Anagnostou, E., & Chau, T. (2013). Statistical persistence and timing characteristics of repetitive circle drawing in children with ASD. *Developmental Neurorehabilitation, 16(4),* 245–254.

Fombonne, E. (2003). The prevalence of autism. *Journal of the American Medical Association*, *289*, 1–3.

Forbes, P. A., Pan, X., & de C Hamilton, A. F. (2016). Reduced Mimicry to Virtual Reality Avatars in Autism Spectrum Disorder. *Journal of Autism and Developmental Disorders, 46(12),* 3788–3797.

Forti, S., Valli, A., Perego, P., Nobile, M., Crippa, A., & Molteni, M. (2011). Motor planning and control in autism. A kinematic analysis of preschool children. *Research in Autism Spectrum Disorder. Volume 5,* 834–842.

Foster, N. C. (2019). *Sensorimotor Learning and Control in Autism Spectrum Disorders: The Role of Sensorimotor Integration* (Order No. 28328112). Available from ProQuest Central; ProQuest Dissertations & Theses Global. (2494950149). https://www.proquest.com/dissertations-theses/sensorimotor-learning-control-autism-spectrum/docview/2494950149/se-2

Foster, N. C., Bennett, S. J., Causer, J., Elliott, D., Bird, G. & Hayes, S. J. (2020a). Getting off to a shaky start: Specificity in planning and feedforward control during sensorimotor learning in autism spectrum disorder. *Autism Research, 13*, 423–435.

Foster, N. C., Bennett, S. J., Causer, J., Elliott, D., Bird, G., & Hayes, S. J. (2020b). Facilitating sensorimotor integration via blocked practice underpins imitation learning of atypical biological kinematics in autism spectrum disorder. *Autism: the International Journal of Research and Practice, 24(6),* 1494–1505.

Fournier, K. A. (2008). *Static and dynamic balance control in children with autism spectrum disorders* (Order No. 3416439). Available from ProQuest Dissertations & Theses Global. (741238920). https://www.proquest.com/dissertations-theses/static-dynamic-balance-control-children-with/docview/741238920/se-2

Fournier, K. A., Hass, C. J., Naik, S. K., Lodha, N., & Cauraugh, J. H. (2010). Motor coordination in autism spectrum disorders: A synthesis and meta-analysis. *Journal of Autism and Developmental Disorders, 40(10),* 1227–1240.

Frederickson N., Jones A. P., & Lang J. (2010). Inclusive provision options for pupils on the autistic spectrum. *Journal of Research in Special Educational Needs*, *10(2),* 63–73.

Frolek Clark, G., & Luze, G. (2014). Predicting Handwriting Performance in Kindergarteners Using Reading, Fine-Motor, and Visual-Motor Measures. *Journal of Occupational Therapy, Schools, & Early Intervention*, *7(1),* 29–44.

Fuentes, C., Mostofsky, S., & Bastian, A. (2009). Children with autism show specific handwriting impairments. *Neurology, 73(19)*, 1532–1537.

Fukui, T., Sano, M., Tanaka, A., Suzuki, M., Kim, S., Agarie, H., Fukatsu, R., Nishimaki, K., Nakajima, Y., & Wada, M. (2018). Older Adolescents and Young Adults With Autism Spectrum Disorder Have Difficulty Chaining Motor Acts When Performing Prehension Movements Compared to Typically Developing Peers. F*rontiers in Human Neuroscience, 12,* 430.

Fulceri, F., Tonacci, A., Lucaferro, A., Apicella, F., Narzisi, A., Vincenti, G., Muratori, F., & Contaldo, A. (2018). Interpersonal motor coordination during joint actions in children

with and without autism spectrum disorder: The role of motor information. *Research in Developmental Disabilities, 80,* 13–23.

Gamez Corral, A.S. (2017). A Novel Approach to Enhancing Upper Extremity Coordination in Children with Autism Spectrum Disorder. Available from University of Texas at El Paso DigitalCommons@UTEP, Open Access Theses & Dissertations. https://scholarworks.utep.edu/cgi/viewcontent.cgi?article=1449&context=open_etd

Gandotra, A., Kótyuk, E., Szekely, A., Kasos, K., Csirmaz, L., & Cserjesi, R. (2020). Fundamental movement skills in children with autism spectrum disorder: A systematic review. *Research in Autism Spectrum Disorders, 78(3),* 101632.

Ganglmayer, K., Attig, M., Daum, M. M., & Paulus, M. (2019). Infants' perception of goal-directed actions: A multi-lab replication reveals that infants anticipate paths and not goals. *Infant Behaviour & Development*, *57,* 101340.

Gauthier, S., Anzalone, S. M., Cohen, D., Zaoui, M., Chetouani, M., Villa, F., Berthoz, A., & Xavier, J. (2018). Behavioral Own-Body-Transformations in Children and Adolescents With Typical Development, Autism Spectrum Disorder, and Developmental Coordination Disorder. *Frontiers in Psychology, 9*, 676.

Georgopoulos, A. P., & Grillner, S. (1989). Visuomotor coordination in reaching and locomotion. *Science (New York, N.Y.)*, *245(4923),* 1209–1210.

Gernsbacher, M. A., Sauer, E. A., Geye, H. M., Schweigert, E. K., & Hill Goldsmith, H. (2008). Infant and toddler oral- and manual-motor skills predict later speech fluency in autism. *Journal of Child Psychology and Psychiatry, and Allied Disciplines, 49(1),* 43–50.

Ghaziuddin, M., & Butler, E. (1998). Clumsiness in autism and Asperger syndrome: a further report. *Journal of Intellectual Disability Research : JIDR, 42 (Pt 1),* 43–48.

Gidley Larson, J. C., & Mostofsky, S. H. (2008). Evidence that the pattern of visuomotor sequence learning is altered in children with autism. *Autism Research : Official Journal of the International Society for Autism Research, 1(6),* 341–353.

Gidley Larson, J.C., Bastian, A.J., Donchin, O., Shadmehr, R., & Mostofsky, S.H. (2008). Acquisition of internal models of motor tasks in children with autism. *Brain. 131(Pt 11):*2894-903.

Gidley Larson, J. C., & Suchy, Y. (2014). Does language guide behaviour in children with autism?. *Journal of Autism and Developmental Disorders, 44(9),* 2147–2161.

Gioia, G. A., Isquith, P. K., Guy, S. C., & Kenworthy, L. (2015). *BRIEF-2, Behaviour Rating Inventory of Executive Function (2nd Ed.).* Lutz, FL: Par.

Gioia, G. A., Isquith, P. K., Guy, S. C., & Kenworthy, L. (2000). *Behaviour Rating Inventory of Executive Function.* Odessa, FL: Psychological Assessment Resources.

Glazebrook, C.M., Elliott, D., & Lyons, J. (2006). A kinematic analysis of how young adults with and without autism plan and control goal-directed movements. *Motor Control. Jul;10(3):*244-64.

Glazebrook, C. M., Elliott, D., & Lyons, J. (2008). Temporal judgements of internal and external events in persons with and without autism. *Consciousness and Cognition*, *17(1),* 203–209.

Glazebrook, C., Gonzalez, D., Hansen, S., & Elliott, D. (2009). The role of vision for online control of manual aiming movements in persons with autism spectrum disorders. *Autism. 13(4):*411-433.

Godde, A., Tsao, R., Gepner, B., & Tardif, C. (2018). Characteristics of handwriting quality and speed in adults with autism spectrum disorders. *Research in Autism Spectrum Disorders*, *46,* 19-28.

Goldet, G., & Howick, J. (2013). Understanding GRADE: an introduction. *Journal of Evidence-based Medicine, 6(1),* 50–54.

González H. F., Malpeli A., Etchegoyen G., Lucero L., Romero F., Lagunas C., Lailhacar G., Olivares M., & Uauy R. (2007), Acquisition of visuomotor abilities and intellectual quotient in children aged 4–10 years: relationship with micronutrient nutritional status, *Biological Trace Element Research.120*, no. 1–3, 92–101,

Gough, P. B., & Tunmer, W. E. (1986). Decoding, reading, and reading disability. *Remedial and Special Education*, *7*, 6-10.

Gough, P.B. (1996). How children learn to read and why they fail. *Annals of Dyslexia*, *46(1),* 1–20.

Gowen, E., & Hamilton, A. (2013). Motor abilities in autism: a review using a computational context. *Journal of Autism and Developmental Disorders, 43(2),* 323–344.

Gowen, E., Vabalas, A., Casson, A. J., & Poliakoff, E. (2020). Instructions to attend to an observed action increase imitation in autistic adults. *Autism: the International Journal of Research and Practice, 24(3),* 730–743.

Grace, N., Enticott, P. G., Johnson, B. P., & Rinehart, N. J. (2017). Do Handwriting Difficulties Correlate with Core Symptomology, Motor Proficiency and Attentional Behaviours?. *Journal of Autism and Developmental Disorders, 47(4),* 1006–1017.

Grace, N., Johnson, B. P., Rinehart, N. J., & Enticott, P. G. (2018). Are motor control and regulation problems part of the AUTISM motor profile? A handwriting study. *Developmental Neuropsychology, 43(7),* 581–594.

Graesser, A. C., Singer, M., & Trabasso, T. (1994). Constructing inferences during narrative text comprehension. *Psychological Review*, *101(3),* 371–395.

Graham, S., Berninger, V. W., Weintraub, N., & Schafer, W. (1998). Development of handwriting speed and legibility in grades 1–9. *Journal of Educational Research*, *92,* 42–56.

Graham, S., Liu, X., Bartlett, B., Ng, C., Harris, K. R., Aitken, A., Barkel, A., Kavanaugh C., & Talukdar, J. (2018). Reading for writing: A meta-analysis of the impact of reading interventions on writing. *Review of Educational Research, 88*, 243–284.

Graham, S., Bollinger, A., Olson, C. B., D'Aoust, C., MacArthur, C., McCutchen, D., & Olinghouse, N. (2012). Teaching elementary school students to be effective writers: A practice guide. *NCEE 2012–4058. Washington D.C.: What Works Clearinghouse.*

Green, D., Baird, G., Barnett, A. L., Henderson, L., Huber, J., & Henderson, S. E. (2002). The severity and nature of motor impairment in Asperger's syndrome: A comparison with specific developmental disorder of motor function. Journal of C*hild Psychology and Psychiatry*, *43*, 655–668.

Green, D., Charman, T., Pickles, A., Chandler, S., Loucas, T., Simonoff, E., & Baird, G. (2009). Impairment in movement skills of children with autistic spectrum disorders. *Developmental Medicine and Child Neurology, 51(4),* 311–316.

Greenstein, A. (2016). *Radical Inclusive Education: Disability, Teaching and Struggles for Liberation*. Routledge.

Grissmer, D., Grimm, K. J., Aiyer, S. M., Murrah, W. M., & Steele, J. S. (2010). Fine motor skills and early comprehension of the world: Two new school readiness indicators. *Developmental Psychology, 46(5),* 1008–1017.

Grömping, U. (2015). Variable importance in regression models. *Wiley Interdisciplinary Reviews: Computational Statistics* 7, 137–152.

Hair, J. F., Anderson, R. E., Tatham, R. L., & Black, W. C. (1995). M*ultivariate Data Analysis.* Englewood Cliffs, NJ Prentice-Hall.

Hallett, M., Lebiedowska, M. K., Thomas, S. L., Stanhope, S. J., Denckla, M. B., & Rumsey, J. (1993). Locomotion of autistic adults. *Archives of neurology, 50(12),* 1304–1308.

Hannant, P., Cassidy, S., Tavassoli, T., & Mann, F. (2016). Sensorimotor Difficulties Are Associated with the Severity of Autism Spectrum Conditions. Frontiers in Integrative Neuroscience, 10, 28.

Happé, F., Cook, J., & Bird, G. (2017). The structure of social cognition: In(ter)dependence of Sociocognitive Processes. *Annual Review of Psychology, 68*:243-267

Harris, J., Cale, L., & Musson, H. (2012). The predicament of primary physical 8 education: a consequence of 'insufficient 'ITT and 'ineffective' CPD? *Physical 9 Education and Sport Pedagogy, 17(4),* 367-381.

Harris J. (2018). Leo Kanner and autism: a 75-year perspective. *International Review of Psychiatry (Abingdon, England), 30(1),* 3–17.

Hasan, C. Z. C., Jailani, R., Tahir, N. M., Yassin, I. M. & Rizman, Z. I. (2017). Automated classification of autism spectrum disorders gait patterns using discriminant analysis based on kinematic and kinetic gait features. *Journal of Applied Environmental and Biological Science. 7*, 150–156.

Hastie, P. A., & Hay, P. (2012). Chapter 7. Qualitative approaches. In K. Armour & D. Macdonald (Eds.), *Research Methods in Physical Education and Youth Sport (pp. 79-94).* London: Routledge.

Haswell, C.C., Izawa, J., Dowell, L.R., Mostofsky, S.H., & Shadmehr, R. (2009). Representation of internal models of action in the autistic brain. *Nature Neuroscience, 12(8),* 970–972.

Hayes, S. J., Elliot, D., & Bennett, S. J. (2010). General motor representations are developed during action-observation. *Experimental Brain Research 204*, 199–206.

Hayes, S. J., Andrew, M., Elliott, D., Gowen, E., & Bennett, S. J. (2016). Low Fidelity Imitation of Atypical Biological Kinematics in Autism Spectrum Disorders Is Modulated by Self-Generated Selective Attention. *Journal of Autism and Developmental Disorders, 46(2),* 502–513.

Hayes, S. J., Andrew, M., Foster, N. C., Elliott, D., Gowen, E., & Bennett, S. J. (2018). Sensorimotor learning and associated visual perception are intact but unrelated in autism spectrum disorder. *Autism Research, 11(2),* 296–30

Healy, S., Nacario, A., Braithwaite, R. E., & Hopper, C. (2018). The effect of physical activity interventions on youth with autism spectrum disorder: A meta-analysis. *Autism Research: Official Journal of the International Society for Autism Research*, *11(6),* 818–833.

Hellendoorn, A., Wijnroks, L., van Daalen, E., Dietz, C., Buitelaar, J., & Leseman, P. (2015). Motor functioning, exploration, visuospatial cognition and language development in preschool children with autism. *Research in Developmental Disabilities*, *39,* 32–42.

Hellinckx, T., Roeyers, H., & Van Waelvelde, H. (2013). Predictors of handwriting in children with autism spectrum disorder. *Research in Autism Spectrum Disorders*, *7(1),* 176–186.

Holgersson, T., Nordström, L., & Öner, Ö. (2015). On regression modelling with dummy variables versus separate regressions per group: comment on Holgersson et al. *Journal of Applied Statistics*, *43(8),* 1564–1565.

Honda, H., Shimizu, Y., Misumi, K., Niimi, M., & Ohashi, Y. (1996). Cumulative incidence and prevalence of childhood autism in children in Japan. *British Journal of Psychiatry*, *169,* 228–235.

Hoover, W. A., Gough, P. B., & Dombey, H. (1990). The Simple View of Reading. *Reading and Writing: An Interdisciplinary Journal, 2, 127–160.* Retrieved from http://www.ite.org.uk/ite_readings/simple_view_reading.pdf

Hopkins, S., Black, A. A., White, S. L. J., & Wood, J. M. (2019). Visual information processing skills are associated with academic performance in Grade 2 school children. *Acta Ophthalmologica*, *97(8),* e1141–e1148.

Houwen, S., Visser, L., van der Putten, A., & Vlaskamp, C. (2016). The interrelationships between motor, cognitive, and language development in children with and without intellectual and developmental disabilities. *Research in Developmental Disabilities*, *53-54*, 19–31.

Hudson, K. N., Ballou, H. M., & Willoughby, M. T. (2021). Short report: Improving motor competence skills in early childhood has corollary benefits for executive function and numeracy skills. *Developmental Science, 24(4),* e13071.

Iacoboni M. (2009). Imitation, empathy, and mirror neurons. *Annual Review of Psychology, 6*0: 653-670.

Iverson, J. M., Northrup, J. B., Leezenbaum, N. B., Parladé, M. V., Koterba, E. A., & West, K. L. (2018). Early gesture and vocabulary development in infant siblings of children with autism spectrum disorder. *Journal of Autism & Developmental Disorders*, *48*, 55–71

Izawa, J., Pekny, S., Marko, M.K., Haswell, C.C., Shadmehr, R., & Mostofsky, S.H. (2012). Motor learning relies on integrated sensory inputs in ADHD, but over-selectivity on proprioception in autism spectrum conditions. *Autism Research*, *5*, 124–136.

Janse, R. J., Hoekstra, T., Jager, K. J., Zoccali, C., Tripepi, G., Dekker, F. W., & Van Diepen, M. (2021). Conducting correlation analysis: important limitations and pitfalls. *Clinical Kidney Journal, 14(11),* 2332–2337.

Jasmin,E M. Couture, P. McKinley, G. Reid, E. Fombonne, E. Gisel (2009). Sensorimotor and daily living skills of preschool children with autism spectrum disorders. *Journal of Autism and Developmental Disorders, 39 (2)*, pp. 231-241

Jiménez, L., Lorda, M. J., & Méndez, C. (2014). Emulation and mimicry in school students with typical development and with high functioning autism. *Journal of Autism and Developmental Disorders, 44(7),* 1597–1608.

Johnston M. V. (2004). Clinical disorders of brain plasticity. *Brain & Development, 26(2),* 73–80.

Johnson, B. P., Papadopoulos, N., Fielding, J., Tonge, B., Phillips, J. G., & Rinehart, N. J. (2013). A quantitative comparison of handwriting in children with high- functioning autism and attention deficit hyperactivity disorder. *Research in Autism Spectrum Disorders, 7(12),* 1638-1646.

Johnson, B., Phillips, J., Papadopoulos, N., Fielding, J., Tonge, B., & Rinehart, N. J. (2015). Do children with autism and Asperger's disorder have difficulty controlling

handwriting size? A kinematic evaluation. *Research in Autism Spectrum Disorders,11*, 20–26.

Kadam, P., & Bhalerao, S. (2010). Sample size calculation. *International Journal of Ayurveda Research, 1(1),* 55–57.

Kaiser, H.F. (1974). “An Index of Factorial Simplicity.” *Psychometrika 39 (1):* 31–36.

Kaiser, M. L., Albaret, J. M., & Doudin, P. A. (2009). Relationship Between Visual-Motor Integration, Eye-Hand Coordination, and Quality of Handwriting. *Journal of Occupational Therapy, Schools, & Early Intervention*, *2(2),* 87–95.

Kanner, L. (1943). Autism disturbances of affective contact. *Nervous Child, 2*, 217–250.

Kaur, M., M Srinivasan, S., & N Bhat, A. (2018). Comparing motor performance, praxis, coordination, and interpersonal synchrony between children with and without Autism Spectrum Disorder (ASD). *Research in Developmental Disabilities, 72,* 79–95.

Keele, S. W. (1968). Movement control in skilled motor performance. *Psychological Bulletin, 70*(6, Pt.1), 387–403.

Kelley, K., Lai, K., & Wu, P.J. (2008). Using R for data analysis: A best practice for research. In J. W. Osborne (Ed.), *Best Practices in Quantitative Methods* (p. 535-

572). Thousand Oaks, CA: Sage.

Kenny, L., Hattersley, C., Molins, B., Buckley, C., Povey, C., & Pellicano, E. (2016). Which terms should be used to describe autism? Perspectives from the UK autism community. *Autism*, *20(4),* 442-462.

Keysers, C., Paracampo, R., & Gazzola, V. (2018). What neuromodulation and lesion studies tell us about the function of the mirror neuron system and embodied cognition. *Current Opinion in Psychology, 24*, 35–40.

Khan, M. A., Hale, T., Garry, M.I,. & Franks, I. M. (2002). Separate sources of spatial information for distance and location in rapid aiming movements. *Motor Control 6*, 84–103.

Khatib, L., Li, Y., Geary, B., & Popov, V. (2022). Meta-analysis on the relation between visuomotor integration and academic achievement: Role of educational stage and disability. *Educational Review Research, 3*5, 1–20.

Kim, Y. S., Otaiba, S. A., Sidler, J. F., & Gruelich, L. (2013). Language, literacy, attentional behaviours, and instructional quality predictors of written composition for first graders. *Early Childhood Research Quarterly*, *28(3),* 461–469.

Klingner, J. K., Artiles, A. J., & Méndez Barletta, L. (2006). English language learners who struggle with reading: Language acquisition or learning disabilities? *Journal of Learning Disabilities, 39*, 108-128.

Kim, H., Duran, C. A., Cameron, C. E., & Grissmer, D. (2018). Developmental relations among motor and cognitive processes and mathematics skills. *Child Development, 89,* 476–494.

Kmet L., Lee R. C., Cook L. S., Lorenzetti D., Godlovitch G., & Einsiedel E. (2004). *Systematic Review of the Social, Ethical, and Legal Dimensions of Genetic Cancer Risk Assessment Technologies*. Calgary: Alberta Heritage Foundation for Medical Research (AHFMR).

Knekta, E., Runyon, C., & Eddy, S. (2019). One Size Doesn't Fit All: Using Factor Analysis to Gather Validity Evidence When Using Surveys in Your Research. *CBE Life Sciences Education*, *18(1),* rm1.

Koenig A. J., Rex E. J., Wormsley D. P., Baker R. L. (1994). *Foundations of Braille Literacy*. New York, NY: AFB Press.

Kolt, G. S., Schofield, G. M., McLachlan, C., Oliver, M., Lucas, P., & Maddison, R. (2005). Active movement scoping exercise and programme evaluation – Report to Sport and Recreation. New Zealand, Auckland. *Auckland University of Technology.*

Korkman M., Kirk U., & Kemp S. (2007). *NEPSY – Second Edition (NEPSY-II)*. Harcourt Assessment.

Kostrubiec, V., Huys, R., Jas, B., & Kruck, J. (2018). Age-dependent Relationship Between Socio-adaptability and Motor Coordination in High Functioning Children with Autism Spectrum Disorder. *Journal of Autism and Developmental Disorders, 48(1),* 209–224.

Krishnan-Barman, S., Forbes, P. A., & Hamilton, A. F. D. C. (2017). How can the study of action kinematics inform our understanding of human social interaction? *Neuropsychologia*, *105,* 101–110

Kwakye, L. D., Foss-Feig, J. H., Cascio, C. J., Stone, W. L., & Wallace, M. T. (2011). Altered auditory and multisensory temporal processing in autism spectrum disorders. *Frontiers in integrative neuroscience, 4*, 129.

Landers, D. M., Alderman, B. L., & Rogers, T. J. (2003). School policy makers' views of the importance of physical education in the curriculum (Peer-Reviewed Symposia). *Research Quarterly for Exercise and Sport, 74*, 98-100.

Landa, R. J., Reetzke, R., Holingue, C. B., Herman, D., & Hess, C. R. (2022). Diagnostic stability and phenotypic differences among school-age children diagnosed with ASD before age 2. *Frontiers in Psychiatry, 13,* 805686.

Lang, R., Regester, A., Lauderdale, S., Ashbaugh, K., & Haring, A. (2010). Treatment of anxiety in autism spectrum disorders using cognitive behaviour therapy: A systematic review. *Developmental Neurorehabilitation*, *13(1),* 53–63.

Lovaas, N. W. & Eikeseth, S. (2003). Reading and writing: a brief introduction. In OJ. Lovaas (Ed.), *Teaching Individuals with Developmental Delays: Basic Intervention Techniques* (pp. 271-289). Austin, TX: Pro-Ed.

Lê, M., Quémart, P., Potocki, A., Gimenes, M., Chesnet, D., & Lambert, E. (2021). Modeling the influence of motor skills on literacy in third grade: Contributions of executive functions and handwriting. *PloS One, 16(11)*, e0259016.

LeBarton, E. S., & Landa, R. J. (2019). Infant motor skill predicts later expressive language and autism spectrum disorder diagnosis. *Infant Behaviour and Development,* 54, 37–47.

Leedy, P. D., & Ormrod, J. E. (2005). Practical research (Vol. 108). *Saddle River,* NJ: Pearson Custom

Leekam, S. R., Prior, M. R., & Uljarevic, M. (2011). Restricted and repetitive behaviors in autism spectrum disorders: a review of research in the last decade. *Psychological Bulletin, 137(4),* 562–593.

Lehrl, S., Kluczniok, K., & Rossbach, H.G. (2016). Longer-term associations of preschool education: The predictive role of preschool quality for the development of

mathematical skills through elementary school. *Early Childhood Research Quarterly*, *36*, 475-488.

Leonard, H. C., Bedford, R., Pickles, A., & Hill, E. L. (2015). Predicting the rate of language development from early motor skills in at-risk infants who develop autism spectrum disorder. *Research in Autism Spectrum Disorders*, 13–14, 15–24.

Li, Q., Han, Y., Dy, A., & Hagerman, R. J. (2017). The Gut Microbiota and Autism Spectrum Disorders. *Frontiers in Cellular Neuroscience, 11,* 120.

Li-Tsang, C. W., Li, T. M., Ho, C. H., Lau, M. S., & Leung, H. W. (2018). The relationship between sensorimotor and handwriting performance in Chinese adolescents with autism spectrum disorder. *Journal of Autism and Developmental Disorders, 48(9),* 3093–3100.

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P., Clarke, M., Devereaux, P. J., Kleijnen, J., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. *PLoS medicine, 6(7),* e1000100.

Licari, M. K., Alvares, G. A., Varcin, K., Evans, K. L., Cleary, D., Reid, S. L., Glasson, E. J., Bebbington, K., Reynolds, J. E., Wray, J., & Whitehouse, A. J. O. (2020).

Prevalence of Motor Difficulties in Autism Spectrum Disorder: Analysis of a Population-Based Cohort. *Autism Research: Official Journal of the International Society for Autism Research, 13(2),* 298–306.

Lidstone, D. E., Miah, F. Z., Poston, B., Beasley, J. F., Mostofsky, S. H., & Dufek, J. S. (2020). Children with Autism Spectrum Disorder Show Impairments During Dynamic Versus Static Grip-force Tracking. *Autism Research: Official Journal of the International Society for Autism Research, 13(12),* 2177–2189.

Lidstone, D. E., & Mostofsky, S. H. (2021). Moving Toward Understanding Autism: Visual-Motor Integration, Imitation, and Social Skill Development. *Pediatric neurology, 122,* 98–105.

Lindsay, G. (2007). Educational Psychology and the Effectiveness of Inclusive Education/Mainstreaming. *British Journal of Educational Psychology, 77 (1):* 1–24.

Lim, Y. H., Licari, M., Spittle, A. J., Watkins, R. E., Zwicker, J. G., Downs, J., & Finlay-Jones, A. (2021). Early Motor Function of Children With Autism Spectrum Disorder: A Systematic Review. *Pediatrics*, *147(2),* e2020011270.

Linkenauger, S. A., Lerner, M. D., Ramenzoni, V. C., & Proffitt, D. R. (2012). A perceptual-motor deficit predicts social and communicative impairments in individuals with autism spectrum disorders. *Autism Research: Official Journal of the International Society for Autism Research, 5(5),* 352–362.

Liu, Y., Tang, Y., Cao, Z. B., Chen, P. J., Zhang, J. L., Zhu, Z., Zhuang, J., Yang, Y., & Hu, Y. Y. (2016). Results From Shanghai's (China) 2016 Report Card on Physical Activity for Children and Youth. *Journal of Physical Activity & Health, 13(11 Suppl 2),* S124–S128.

Lonigan, C. J., Burgess, S. R., & Schatschneider, C. (2018). Examining the simple view of reading with elementary school children: Still simple after all these years. *Remedial and Special Education*, *39(5),* 260–273.

Longcamp, M., Richards, T. L., Velay, J. L., & Berninger, V. W. (2016). Neuroanatomy of handwriting and related reading and writing skills in adults and children with and without learning disabilities: *French-American Connections. Pratiques*, *1*, 171–172.

Lord, C., & Bishop, S. L. (2015). Recent advances in autism research as reflected in DSM-5 criteria for autism spectrum disorder. *Annual review of clinical psychology, 11,* 53–70.

Lotter, V. (1966). Epidemiology of autistic conditions in young children. *Social Psychiatry, 1(3),* 124-135.

Loveland, K. A., Tunali-Kotoski, B., Pearson, D. A., Brelsford, K. A., Ortegon, J., & Chen, R. (1994). Imitation and expression of facial affect in autism. *Development and Psychopathology, 6(3),* 433–444.

Lucas, P.J., Baird, J., Arai, L., Law, C., & Roberts, H.M. (2007). Worked Examples of Alternative Methods for the Synthesis of Qualitative and Quantitative Research in Systematic Reviews. *BMC Medical Research Methodology, 7* (1): 4.

Lyons, J. L., Hansen, S., Hurding, S., & Elliott, D. (2006). Optimizing rapid aiming behavior: Movement kinematics depend on the cost of corrective modifications. *Experimental Brain Research*, *174*, 95-100.

MacKinnon, D. P., Fairchild, A. J., & Fritz, M. S. (2007). Mediation analysis. *Annual Review of Psychology*, *58*, 593–614.

MacDonald, M., Lord, C., & Ulrich, D. A. (2013). The Relationship of Motor Skills and Social Communicative Skills in School-Aged Children with Autism Spectrum Disorder. *Adapted Physical Activity Quarterly, 30(3),* 271-282.

Maher, A., & Hayley, F. (2020). The Initial Teacher Education and Continued Professional Development of Special School Physical Education Teachers. *Curriculum Studies in Health and Physical Education 11 (1):* 18–33.

Mari, M., Castiello, U., Marks, D., Marraffa, C., & Prior, M. (2003). The reach-to-grasp movement in children with autism spectrum disorder. Philosophical transactions of the Royal Society of London. *Series B, Biological sciences, 358(1430),* 393–403.

Marko, M. K., Crocetti, D., Hulst, T., Donchin, O., Shadmehr, R., & Mostofsky, S. H. (2015). Behavioural and neural basis of anomalous motor learning in children with autism. *Brain, 138(Pt 3),* 784–797.

Marr, B., Gupta, O., Pike, S., & Roos, G. (2003). Intellectual capital and knowledge management effectiveness. *Management. Decision*. *41*, 771–781.

Marr, D., & Dimeo, S. B. (2006). Outcomes associated with a summer handwriting course for elementary students. *The American Journal of Occupational Therapy: Official Publication of the American Occupational Therapy Association*, *60(1),* 10–15.

Mayes, S.D., & Calhoun, S.L. (2007)。 Learning, attention, writing, and processing speed in typical children and children with ADHD, autism, anxiety, depression, and oppositional-defiant disorder. *Child Neuropsychology* 13: 469–493.

McCandless, L.C., Gustafson, P., Levy, A.R., & Richardson, S. (2012). Hierarchical priors for bias parameters in Bayesian sensitivity analysis for unmeasured confounding. *Statistics in Medicine,31(4),* 383–96.

McHugh M. L. (2012). Interrater reliability: the kappa statistic. Biochemia Medica, 22(3), 276–282.

McLachlan, C., Fleer, M., & Edwards, S. (2013). *Early childhood curriculum:*

Planning, assessment and implementation (2nd Edition.). Melbourne, VIC: Cambridge University Press

Medwell, J., Strand, S., & Wray, D. (2009). The links between handwriting and composing for Y6 children. *Cambridge Journal of Education*, *39(3),* 329–344.

Meyer, B. N., Ferrigni, N. R., Putnam, J. E., Jacobsen, L. B., Nichols, D. E., & McLaughlin, J. L. (1982). Brine shrimp: a convenient general bioassay for active plant constituents. *Planta Medica*, *45(5),* 31–34.

Meyer, D. E., Abrams, R. A. Kornblum, S., Wright, C. E., & Smith, J. E. K. (1988) Optimality in human motor performance: Ideal control of rapid aimed movements. *Psychological Review*, *95(3),* 340-370.

Miller, A. J. (1984). Selection of subsets of regression variables (with discussion). *Journal of the Royal Statistical Society Series A.147:* 389–425.

Miller, H. L., Sherrod, G. M., Mauk, J. E., Fears, N. E., Hynan, L. S., & Tamplain, P. M. (2021). Shared Features or Co-occurrence? Evaluating Symptoms of Developmental Coordination Disorder in Children and Adolescents with Autism Spectrum Disorder. *Journal of Autism and Developmental Disorders*, *51*(10), 3443–3455.

Miller H. L., Licari, M. K., Bhat A., Aziz-Zadeh L. S., Van Damme T., Fears N. E., Cermak S. A., & Tamplain, P. M. (2024). Motor problems in autism: Co-occurrence or feature? *Developmental Medicine and Child Neurology*. Advance online publication.

Minshew, N. J., Sung, K., Jones, B. L., & Furman, J. M. (2004). Underdevelopment of the postural control system in autism. *Neurology, 63*, 2056–2061.

Milne, E., Gomez, R., & Giannadou, A. (2019). Atypical EEG in autism spectrum disorder: Comparing a dimensional and a categorical approach. *Journal of Abnormal Psychology*. ISSN 0021-843X

Miyahara, M., Tsujii, M., Hori, M., Nakanishi, K., Kageyama, H., & Sugiyama, T. (1997). Brief report: motor incoordination in children with Asperger syndrome and learning disabilities. *Journal of Autism and Developmental Disorders*, *27*, 595–603.

Moats, L. (2005). How spelling supports reading: And why it is more regular and predictable than you may think. *American Educator, Winter*, 12–43.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & PRISMA Group. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Medicine*, *6(7),* e1000097.

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L. A., & PRISMA-P Group. (2015). Preferred reporting items for systematic

review and meta-analysis protocols (PRISMA-P) 2015 statement. *Systematic Reviews*, 4(1), 1.

Molinari, M., & Masciullo, M. (2019). The Implementation of Predictions During Sequencing. *Frontiers in Cellular Neuroscience*, *13*, 439.

Morgan, P., & Bourke, S. (2008). Non-specialist Teachers' Confidence to Teach PE: The Nature and Influence of Personal School Experiences in PE. *Physical Education and Sport Pedagogy 13 (1):* 1–29.

Morimoto, C., Hida, E., Shima, K., & Okamura, H. (2018). Temporal Processing Instability with Millisecond Accuracy is a Cardinal Feature of Sensorimotor Impairments in Autism Spectrum Disorder: Analysis Using the Synchronized Finger-Tapping Task. *Journal of Autism and Developmental Disorders, 48(2),* 351–360.

Morimoto, C., Nakazono, S., Kobori, S., Kaneko, F., Muratake, S., & Okamura, H. (2020). Easy assessment of individuals with various severities of autism spectrum disorder, focusing on motor timing control. *Research in Autism Spectrum Disorders, 79.* 101682.

Morley, D., Banks, T., Haslingden, C., Kirk, B., Parkinson, S., Van Rossum, T., Morley, I., & Maher, A. (2021). Including pupils with special educational needs and/or disabilities in mainstream secondary physical education: A revisit study. *European*

Physical Education Review, 27(2), 401–418.

Mosconi, M. W., Luna, B., Kay-Stacey, M., Nowinski, C. V., Rubin, L. H., Scudder, C., Minshew, N., & Sweeney, J. A. (2013). Saccade adaptation abnormalities implicate dysfunction of cerebellar-dependent learning mechanisms in Autism Spectrum Disorders (AUTISM). *PloS One, 8(5),* e63709.

Mosconi, M. W., Mohanty, S., Greene, R. K., Cook, E. H., Vaillancourt, D. E., & Sweeney, J. A. (2015). Feedforward and feedback motor control abnormalities implicate cerebellar dysfunctions in autism spectrum disorder. *The Journal of Neuroscience: the Official Journal of the Society for Neuroscience, 35(5),* 2015–2025.

Mostofsky, S. H., Goldberg, M. C., Landa, R. J., & Denckla, M. B. (2000). Evidence for a deficit in procedural learning in children and adolescents with autism: implications for cerebellar contribution. *Journal of the International Neuropsychological Society:* JINS, 6(7), 752–759.

Mostofsky, S. H., Dubey, P., Jerath, V. K., Jansiewicz, E. M., Goldberg, M. C., & Denckla, M. B. (2006). Developmental dyspraxia is not limited to imitation in children with autism spectrum disorders. *Journal of the International Neuropsychological Society : JINS*, 12(3), 314–326.

Mostofsky, S.H., & Ewen, J.B. (2011). Altered connectivity and action model formation in autism is autism. *Neuroscientist*. *17(4):*437-48.

Mukaka M. M. (2012). Statistics corner: A guide to appropriate use of correlation coefficient in medical research. *Malawi Medical Journal: the Journal of Medical Association of Malawi*, *24(3),* 69–71.

Mulaik, S. A. (1987). A brief history of the philosophical foundations of exploratory factor analysis. *Multivariate Behavioural Research, 22*(3), 267–305.

Munn, Z., Peters, M. D., Stern, C., Tufanaru, C., McArthur, A., & Aromataris, E. (2018). Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. *BMC Medical Research Methodology, 18*, 1–7.

Mussey, J. L., & Klinger, L.G. (2020). Imitation in ASD: Performance on an imitation choice task. *Research in Autism Spectrum Disorders*, 73:101530.

Muthén, L.K. & Muthén, B.O. (1998-2017). *Mplus User's Guide*. Eighth Edition. Los Angeles, CA: Muthén & Muthén

Myles, B. S., Huggins, A., Rome-Lake, M., Hagiwara, T., Barnhill, G. P., & Griswold, D. E. (2003). Written language profile of children and youth with Asperger syndrome: From research to practice. *Education and Training in Developmental Disabilities*, 362-369.

National Literacy Trust. (n.d.). *What is iteracy?*. National Literacy Trust. Retrieved from:

https://literacytrust.org.uk/information/what-is-literacy/#:~:text=Literacy%20is%20the%20ability%20to,make%20sense%20of%20the%20world.

Nazarali, N., Glazebrook, C. M., & Elliott, D. (2009). Movement planning and reprogramming in individuals with autism. *Journal of Autism and Developmental Disorders, 39(10)*, 1401–1411.

Nebel, M. B., Eloyan, A., Nettles, C. A., Sweeney, K. L., Ament, K., Ward, R. E., Choe, A. S., Barber, A. D., Pekar, J. J., & Mostofsky, S. H. (2016). Intrinsic VisualMotor Synchrony Correlates With Social Deficits in Autism. *Biological Psychiatry*, 79(8), 633–641.

Nemeth, D., Janacsek, K., Balogh, V., Londe, Z., Mingesz, R., Fazekas, M., Jámbori, S., Danyi, I., & Vetró, A.. (2010). Learning in autism: implicitly superb. *PLoS ONE,* 5 (7), e11731.

Newell, K. M. (2020). What are fundamental motor skills and what is fundamental about them? *Journal of Motor Learning and Development*, *8(2),* 280–314.

Nor, M. M., Jailani, R., Tahir, N. M., Yassin, I. M., Rizman, Z. I., & Hidayat, R. (2016). EMG signals analysis of BF and RF muscles in autism spectrum disorder (AUTISM) during walking. *International Journal on Advanced Science, Engineering and Information Technology, 6*(5), 793-798.

O'Leary, M. (2020). *Classroom observation: A guide to the effective observation of teaching and learning – (Second Edition ed.).* Routledge and student-centered learning. *International Journal of Environmental & Science Education*, *10(1),* 87-98.

Odom, A. L., & Bell, C. V. (2015). Associations of Middle School Student Science Achievement and Attitudes about Science with Student-Reported Frequency of Teacher Lecture Demonstrations and Student-Centered Learning. *International Journal of Environmental & Science Education, 10(1),* 87-97

Ofsted (2013). Beyond 2012 – outstanding physical education for all. *Physical Education in Schools 2008-12*.www.ofsted.gov.uk

Ohara, R., Kanejima, Y., Kitamura, M., & Izawa, K. P. (2019). Association between Social Skills and Motor Skills in Individuals with Autism Spectrum Disorder: A Systematic Review. *European Journal of Investigation in Health, Psychology and Education*, *10(1),* 276–296.

Oliver, M., Schofield, G. M., Kolt, G. S., & McLachlan, C. (2007). Physical Activity in Early Childhood: Current State of Knowledge. *New Zealand Research in Early Childhood Education, 10*, 47-68.

Oliveira, F. T., Elliott, D., & Goodman, D. (2005). Energy-minimization bias: compensating for intrinsic influence of energy-minimization mechanisms. *Motor Control, 9(1),* 101–114.

Pagani, L. S., Fitzpatrick, C., Barnett, T. A., & Dubow, E. (2010). Prospective associations between early childhood television exposure and academic, psychosocial, and physical well-being by middle childhood. *Archives of Pediatrics & Adolescent Medicine*, *164(5),* 425–431.

Pagani, L. S., & Messier, S. (2012). Links between motor skills and indicators of school readiness at kindergarten entry in urban disadvantaged children. *Journal of Educational and Developmental Psychology*, *2*, 95–107.

Pan, C., Chu, C. H., Tsai, C. L., Sung, M. C., Huang, C. Y., & Ma, W. Y. (2017). The impacts of physical activity intervention on physical and cognitive outcomes in children with autism spectrum disorder. *Autism, 21*, 190–202.

Papadopoulos, N., McGinley, J., Tonge, B., Bradshaw, J., Saunders, K., Murphy, A., & Rinehart, N. (2012). Motor proficiency and emotional/behavioural disturbance in autism and Asperger's disorder: another piece of the neurological puzzle? *Autism*, *16(6),* 627–640.

Parma, V., Bulgheroni, M., Tirindelli, R., & Castiello, U. (2014). Facilitation of action planning in children with autism: the contribution of the maternal body odour. *Brain and Cognition, 88,* 73–82.

Pearson, J. R. (2020). *A Comparative Assessment of Discrete and Reciprocal Design in Children with Autism Spectrum Disorder* (Order No. 28001753). Available from

ProQuest Dissertations & Theses Global. (2425610468). https://www.proquest.com/dissertations-theses/comparative-assessement-discrete-reciprocal/docview/2425610468/se-2

Pellicano, E., & Gibson, L.Y. (2008). Investigating the functional integrity of the dorsal visual pathway in autism and dyslexia. *Neuropsychologia*. *46(10):*2593-6.

Pellegrino J. W., & Hilton M. L. (2012). *Education for life and work: Developing transferable knowledge and skills in the 21st-century*. *National Academy of Sciences.*

Pellicano, E., Dinsmore, A., & Charman, T. (2014). What should autism research focus upon? Community views and priorities from the United Kingdom. *Autism: the International Journal of Research and Practice, 18(7),* 756–770.

Pierno, A. C., Mari, M., Lusher, D., & Castiello, U. (2008). Robotic movement elicits visuomotor priming in children with autism. *Neuropsychologia, 46(2)*, 448–454.

Poole, D., Gowen, E., Warren, P. A., & Poliakoff, E. (2018). Visual-tactile selective attention in autism spectrum condition: An increased influence of visual distractors. *Journal of Experimental Psychology: General, 147*(9), 1309–1324.

Pratt, J., & Abrams, R.A. (1994). Action-centred inhibition: effects of distractors on movement planning and execution. *Human Movement Science*, *13,* 245–254.

Preacher, K. J., & Kelley, K. (2011). Effect size measures for mediation models: quantitative strategies for communicating indirect effects. *Psychological Methods*, *16(2),* 93–115.

Priest, H., Roberts, P., & Woods, L. (2002). An overview of three different approaches to the interpretation of qualitative data. Part 1: Theoretical issues. *Nurse Researcher, 10(1),* 30–42.

Prinz, W. (1997). Perception and Action Planning. *European Journal of Cognitive Psychology, 9(2),* 129–154.

Puranik, C., & Lonigan, C. (2011). From scribbles to scrabble: Preschool children's developing knowledge of written language. *Reading and Writing: An Interdisciplinary Journal 24*: 567–589.

Radonovich, K. J., Fournier, K. A., & Hass, C. J. (2013). Relationship between postural control and restricted, repetitive behaviours in autism spectrum disorders. *Frontiers in integrative neuroscience, 7*, 28.

Richardson, D. B., Hamra, G. B., MacLehose, R. F., Cole, S. R., & Chu, H. (2015). Hierarchical regression for analyses of multiple outcomes. *American Journal of Epidemiology*, *182(5),* 459–467.

Rinehart, N. J., Bradshaw, J. L., Brereton, A. V., & Tonge, B. J. (2001). Movement preparation in high-functioning autism and Asperger disorder: a serial choice reaction

time task involving motor reprogramming. *Journal of Autism and Developmental Disorders, 31(1),* 79–88.

Rinehart, N. J., Bellgrove, M. A., Tonge, B. J., Brereton, A. V., Howells-Rankin, D., & Bradshaw, J. L. (2006a). An examination of movement kinematics in young people with high-functioning autism and Asperger's disorder: further evidence for a motor planning deficit. *Journal of Autism and Developmental Disorders*, *36(6),* 757-767.

Rinehart, N. J., Tonge, B. J., Iansek, R., McGinley, J., Brereton, A. V., Enticott, P. G., & Bradshaw, J. L. (2006b). Gait function in newly diagnosed children with autism: cerebellar and basal ganglia related motor disorder. *Developmental Medicine & Child Neurology, 48(10),* 819–824.

Rinehart, N. J., Tonge, B. J., Bradshaw, J. L., Iansek, R., Enticott, P. G., & McGinley, J. (2006c). Gait function in high-functioning autism and Asperger's disorder: evidence for basal-ganglia and cerebellar involvement?. *European Child & Adolescent Psychiatry, 15(5),* 256–264.

Roberts, J., Jurgens, J., & Burchinal, M. (2005). The role of home literacy practices in preschool children's language and emergent literacy skills. *Journal of Speech, Language, and Hearing Research: JSLHR, 48(2),* 345–359.

Rogers, S. J., & Pennington, B. F. (1991). A theoretical approach to the deficits in infantile autism. *Development and Psychopathology, 3(2),* 137–162.

Rogers, B. (2003). *Effective Supply Teaching: Behaviour Management, Classroom Discipline and Colleague Support*. London: Paul Chapman Publishing.

Rogers, J. A., Someya, T., & Huang, Y. (2010). Materials and mechanics for stretchable electronics. *Science (New York, N.Y.), 327(5973),* 1603–1607.

Roman-Urrestarazu, A., van Kessel, R., Allison, C., Matthews, F. E., Brayne, C., & Baron-Cohen, S. (2021). Association of Race/Ethnicity and Social Disadvantage With Autism Prevalence in 7 Million School Children in England. *JAMA Pediatrics, 175(6),* e210054.

Rommelse, N., Langerak, I., Van der Meer, J., de Bruijn, Y., Staal, W., & Oerlemans, A. (2015). Intelligence May Moderate the Cognitive Profile of Patients with Autism.

PLoS ONE 10(10): e0138698.

Rosenblum, S., Weiss, P.L., & Parush, S. (2003). Product and process evaluation of handwriting difficulties: A review. *Educational Psychology Review 15(1):* 41–81.

Rosenblum, S., Simhon, H. A. B., & Gal, E. (2016). Unique handwriting performance characteristics of children with high-functioning autism spectrum disorder. *Research in Autism Spectrum Disorders*, *23,* 235-244.

Rosenman, R., Tennekoon, V., & Hill, L. G. (2011). Measuring bias in self-reported data. *International Journal of Behavioural & Healthcare Research, 2(4),* 320–332.

Rosseel, Y. (2012). lavaan An R Package for Structural Equation Modeling. *Journal of Statistical Software, 48*, 1-36.

Rueckriegel, S. M., Blankenburg, F., Henze, G., Baqué, H., & Driever, P. H. (2009). Loss of fine motor function correlates with ataxia and decline of cognition in cerebellar tumor survivors. *Pediatric Blood & Cancer*, *53(3),* 424–431.

Ruggeri, A., Dancel, A., Johnson, R., & Sargent, B. (2020). The effect of motor and physical activity intervention on motor outcomes of children with autism spectrum disorder: A systematic review. *Autism*, *24(3):*544-568.

Sachse, M., Schlitt, S., Hainz, D., Ciaramidaro, A., Schirman, S., Walter, H., Poustka, F., Bölte, S., & Freitag, C. M. (2013). Executive and visuo-motor function in adolescents and adults with autism spectrum disorder. *Journal of Autism and Developmental Disorders, 43(5),* 1222–1235.

Salowitz, N. M., Eccarius, P., Karst, J., Carson, A., Schohl, K., Stevens, S., Van Hecke, A. V., & Scheidt, R. A. (2013). Brief report: visuo-spatial guidance of movement during gesture imitation and mirror drawing in children with autism spectrum disorders. *Journal of Autism and Developmental Disorders*, *43(4*), 985–995.

Salowitz, N. M. G. (2015). *Multimodal sensory integration for perception and action in high functioning children with autism spectrum disorder* (Order No. 3665651). Available from ProQuest Dissertations & Theses Global. (1641131648). https://www.proquest.com/dissertations-theses/multimodal-sensory-integration-perception-action/docview/1641131648/se-2

Sammons, P., Elliot, K., Sylva, M., Melhuish, I., Siraj, I., & Taggart, B. (2004). The Impact of Pre-school on Young Children's Cognitive Attainments at Entry to Reception. *British Education Research Journal 30*: 691–712.

Santi, K. L., Francis, D. J., Currie, D., & Wang, Q. (2015). Visual-motor integration skills: accuracy of predicting reading. *Optometry and Vision Science: Official Publication of the American Academy of Optometry*, *92(2),* 217–226.

Sattar, T., Ullah, M. I., & Ahmad, B. (2022). The Role of Stakeholders Participation, Goal Directness and Learning Context in Determining Student Academic Performance: Student Engagement as a Mediator. *Frontiers in Psychology, 13,* 875174.

Saunders, J. A., & Knill, D. C. (2003). Humans use continuous visual feedback from the hand to control fast reaching movements. *Experimental Brain Research, 152(3),* 341–352.

Schaal, S., Ijspeert, A., & Billard, A. (2003). Computational approaches to motor learning by imitation. *Philosophical Transaction of the Royal Society of London: Series B, Biological Sciences* 358: 537–547.

Schleicher, A. (2019). PISA 2018: Insights and Interpretations. *OECD Publishing*. https://www.oecd.org/pisa/PISA%202018%20Insights%20and%20Interpretations%20 FINAL%20PDF.pdf

Schmidt R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, 82, 225–260.

Schmidt R. A. (2003). Motor schema theory after 27 years: Reflections and implications for a new theory. *Research Quarterly for Exercise and Sport*, *74,* 366–375.

Schopler, E., Reichler, R. J., & Renner, B. R. (1986). *The Childhood Autism Rating Scale (CARS).* Irvington: For diagnostic screening and classification of autism.

Schwartz, C. E., & Sprangers, M. A. (1999). Methodological approaches for assessing response shift in longitudinal health-related quality-of-life research. *Social Science & Medicine (1982), 48(11),* 1531–1548.

Seidenberg, M. S. (2013). The science of reading and its educational implications. *Language Learning and Development*, *9*, 331–360.

Seitz, R. J., & Angel, H.-F. (2020). Belief formation: A driving force for brain evolution. *Brain and Cognition*, *140*, 105548.

Sesma, H. W., Mahone, E. M., Levine, T., Eason, S. H., & Cutting, L. E. (2009). The contribution of executive skills to reading comprehension. *Child Neuropsychology: A Journal on Normal and Abnormal Development in Childhood and Adolescence*, *15(3),* 232–246.

Shafer, R. L. (2019). *Movement Kinematic and Electrophysiological Signatures of Sensorimotor Integration in Autism* (Order No. 13811832). Available from ProQuest Dissertations & Theses Global. (2247912331). https://www.proquest.com/dissertations-theses/movement-kinematic-electrophysiological/docview/2247912331/se-2

Shea, J. B., & Morgan, R. L. (1979). Contextual interference effects on the acquisition, retention, and transfer of a motor skill. *Journal of Experimental Psychology: Human Learning and Memory, 5*(2), 179–187.

Shechtman, Z., & Pastor, R. (2005). Cognitive-Behavioral and Humanistic Group Treatment for Children With Learning Disabilities: A Comparison of Outcomes and Process. *Journal of Counselling Psychology*, *52(3),* 322–336.

Shin, S., Crapse, T. B., Mayo, J. P., & Sommer, M. A. (2009). Visuomotor integration. In *M. D. Binder, N. Hirokawa, & U. Windhorst (Eds.), Encyclopedia of Neuroscience* (pp. 4354–4359).

Shmueli, G. (2010). To explain or to predict? *Statistical Science*, *25(3),* 289-310.

Sinclair, J. (2013). Why I dislike “person first” language. *Autonomy, the Critical Journal of Interdisciplinary Autism Studies,* 1(2).

Singh, J. A., Siddiqi, M., Parameshwar, P., & Chandra-Mouli, V. (2019). World Health Organization Guidance on Ethical Considerations in Planning and Reviewing Research Studies on Sexual and Reproductive Health in Adolescents. *The Journal of Adolescent Health : Official Publication of the Society for Adolescent Medicine, 64(4),* 427–429.

Smith, I. M., & Bryson, S.E. (1998). Gesture imitation in autism I: non-symbolic postures and sequences. *Cognitive Neuropsychology*, *15*, 747–770.

Smith, I. C., Reichow, B., & Volkmar, F. R. (2015). The effects of DSM-5 criteria on number of individuals diagnosed with autism spectrum disorder: A systematic review. *Journal of Autism and Developmental Disorders, 45(8),* 2541–2552.

Smith, R,, Snow, P., & Serry, T. (2021). The role of background knowledge in reading comprehension: A critical review. *Reading Psychology 42(3):* 214–240.

Snedecor, G.W. & Cochran, W.G. (1980). *Statistical Methods. 7th Edition, Iowa State University Press*, Ames.

Snowling, M. J., Stothard, S. E., Clarke, P., Bowyer-Crane, C., Harrington, A., Truelove, E., & Hulme, C. (2012). *York Assessment of Reading for Comprehension (YARC).* GL Assessment.

Solari, E. J., Grimm, R. P., McIntyre, N. S., Zajic, M., & Mundy, P. C. (2019). Longitudinal stability of reading profiles in individuals with higher functioning autism. *Autism: The International Journal of Research and Practice*.

Son, S.H., & Meisels, S. J. (2006). The relationship of young children's motor skills to later reading and math achievement. *Merrill-Palmer Quarterly, 52*(4), 755–778.

Sortwell, A., Forte, P., Ramirez-Campillo, R., Trimble, K., Steel, K., & O'Brien, K. (2022). Interventions to Promote the Development of Motor Performance Skills in Primary SchoolAged Children with Autism Spectrum Disorder: A Systematic Review and Meta-Analysis of Controlled Trials. *International Journal of Kinesiology and Sports Science 10(4):*34–54.

Sowa, M., & Meulenbroek, R. (2012). Effects of physical exercise on autism spectrum disorders: A meta-analysis. *Research in Autism Spectrum Disorders, 6*(1), 46–57.

Sparaci, L., Formica, D., Lasorsa, F. R., Mazzone, L., Valeri, G., & Vicari, S. (2015). Untrivial Pursuit: Measuring Motor Procedures Learning in Children with Autism. *Autism Research: Official Journal of the International Society for Autism Research, 8(4),* 398–411.

Srinivasan, S. M., Cavagnino, D. T., & Bhat, A. N. (2018). Effects of Equine Therapy on Individuals with Autism Spectrum Disorder: A Systematic Review. *Review journal of Autism and Developmental Disorders*, *5(2),* 156–175.

Starkes, J., Helsen, W., & Elliott, D. (2002). A ménage à trois: the eye, the hand and on-line processing. *Journal of Sports Sciences*, *20(3),* 217–224.

Sterne, J. A., Hernán, M. A., Reeves, B. C., Savović, J., Berkman, N. D., Viswanathan, M., Henry, D., Altman, D. G., Ansari, M. T., Boutron, I., Carpenter, J. R., Chan, A. W., Churchill, R., Deeks, J. J., Hróbjartsson, A., Kirkham, J., Jüni, P., Loke, Y. K., Pigott, T. D., Ramsay, C. R., …& Higgins, J. P. (2016). ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. *BMJ (Clinical Research Edition)*, *355*, i4919.

Stevenson, P., Novotny, S., May, J., & Ancell, C. (2015). Comparing Functional Motor Control and Gait Parameters in Children with Autism to those of Age-Matched Peers

who are Typically Developing. *UNLV Theses, Dissertations, Professional Papers, and Capstones*. 2319.

Stewart, H.J., McIntosh, R.D., & Williams, J.H. (2013). A specific deficit of imitation in autism spectrum disorder. *Autism Research. 6(6):522-30*.

Stoit, A. M. B., Van Schie, H. T., Riem, M., Meulenbroek, R. G. J., Newman-Norlund, R. D., Slaats-Willemse, D. I. E., & Buitelaar J. K. (2011). Internal model deficits impair joint action in children and adolescents with autism spectrum disorders. *Research in Autism Spectrum Disorders*, 5, 1526–1537

Stoit, A.M., Van Schie, H.T., Slaats-Willemse, D.I., & Buitelaar, J.K. (2013). Grasping motor impairments in autism: not action planning but movement execution is deficient. *Journal of Autism Developmental Disorder. 43(12).* 2793–806.

Stone, W.L., Ousley, O.Y., & Littleford, C.D. (1997). Motor imitation in young children with autism: What's the object? *Journal of Abnormal Child Psychology*, *25*, 475–485.

Stone, W. L., Coonrod, E. E., & Ousley, O. Y. (2000). Brief report: screening tool for autism in two-year-olds (STAT): development and preliminary data. *Journal of Autism and Developmental Disorders, 30(6),* 607–612.

Storch, S.A., & Whitehurst, G.J. (2002). Oral language and code-related precursors to reading: Evidence from a longitudinal structural model. *Developmental Psychology*, *38(6),* 934–47.

Stuart, M., Stainthorp, R., & Snowling, M. J. (2008). Literacy as a complex activity: Deconstructing the simple view of reading. *Literacy, 42(2),* 59–66.

Taheri-Torbati, H., & Sotoodeh, M. S. (2019). Using video and live modelling to teach motor skill to children with autism spectrum disorder. *International Journal of Inclusive Education, 23*, 405–418.

Tan, B. W., Pooley, J. A., & Speelman, C. P. (2016). A Meta-Analytic Review of the Efficacy of Physical Exercise Interventions on Cognition in Individuals with Autism Spectrum Disorder and ADHD. *Journal of Autism and Developmental Disorders*, *46(9),* 3126–3143.

Taylor B, Jick H, & MacLaughlin D. (2013). Prevalence and incidence rates of autism in the UK: time trend from 2004–2010 in children aged 8 years. *BMJ Open.*

Teitelbaum, P., Teitelbaum, O., Nye, J., Fryman, J., & Maurer, R. G. (1998). Movement analysis in infancy may be useful for early diagnosis of autism. *Proceedings of the National Academy of Sciences of the United States of America, 95(23),* 13982–13987.

Thelwall, M., & Nevill, T. (2021). Is Research with Qualitative Data More Prevalent and Impactful Now? Interviews, Case Studies, Focus Groups and Ethnographies. *Library and Information Science Research*, *43(2),* 101094.

Togo, S., Itahashi, T., Hashimoto, R., Cai, C., Kanai, C., Kato, N., & Imamizu, H. (2019). Fourth finger dependence of high-functioning autism spectrum disorder in multi-digit force coordination. *Scientific Reports, 9(1),* 1737.

Tomasello, M., Carpenter, M., Call, J., Behne, T., & Moll, H. (2005). Understanding and sharing intentions: the origins of cultural cognition. *The Behavioural and Brain Sciences*, *28(5),* 675–735.

Travers, B. G. (2011). *Motor resonance in adolescents and young adults with autism spectrum disorder* (Order No. 3490955). Available from ProQuest Dissertations & Theses Global. (917941621). https://www.proquest.com/dissertations-theses/motor-resonance-adolescents-young-adults-with/docview/917941621/se-2

Travers, B. G., Bigler, E. D., Duffield, T. C., Prigge, M. D. B., Froehlich, A. L., Lange, N., Alexander, A. L., & Lainhart, J. E. (2017). Longitudinal development of manual motor ability in autism spectrum disorder from childhood to mid-adulthood relates to adaptive daily living skills. *Developmental Science, 20(4),* 10.1111/desc.12401.

Tseng, M.H., & Murray, E.A. (1994). Differences in perceptual-motor measures in children with good and poor handwriting. *Occupational Therapy Journal of Research 14*: 19–36.

Vabalas, A., Gowen, E., Poliakoff, E., & Casson, A. J. (2020). Applying Machine Learning to Kinematic and Eye Movement Features of a Movement Imitation Task to Predict Autism Diagnosis. *Scientific reports, 10(1),* 8346.

Van der Smagt, M. J., van Engeland, H., & Kemner, C. (2007). Brief report: Can you see what is not there? Low-level auditory-visual integration in autism spectrum disorder. *Journal of Autism and Developmental Disorders, 37(10),* 2014–2019.

van der Fels, I. M., Te Wierike, S. C., Hartman, E., Elferink-Gemser, M. T., Smith, J., & Visscher, C. (2015). The relationship between motor skills and cognitive skills in 4–16-year-old typically developing children: A systematic review. *Journal of Science and Medicine in Sport, 18(6),* 697–703.

Van Rossum, T., Foweather, L., Richardson, D., Hayes, S., & Morley, D. (2019) Primary Teachers' Recommendations for the Development of a Teacher-Oriented Movement Assessment Tool for 4–7 Years Children, *Measurement in Physical Education and Exercise Science*, *23:2,* 124-134

Van Rossum, T., Foweather, L., Hayes, S., Richardson, D., & Morley, D. (2021) Expert recommendations for the design of a teacher-oriented movement assessment tool for children aged 4-7 years: a Delphi study, *Measurement in Physical Education and Exercise Science*, *25:4,* 283

van Swieten, L. M., van Bergen, E., Williams, J. H., Wilson, A. D., Plumb, M. S., Kent, S. W., & Mon-Williams, M. A. (2010). A test of motor (not executive) planning in developmental coordination disorder and autism. Journal of experimental psychology. *Human Perception and Performance, 36(2),* 493–499.

Van Voorhis, C. R. W., & Morgan, B. L. (2007). Understanding power and rules of thumb for determining sample sizes. *Tutorials in Quantitative Methods for Psychology,* 3(2), 43–50.

Vellutino, F.R., Tunmer, W.E., Jaccard, J., & Chen, R. (2007). Components of reading ability: Multivariate evidence for a convergent skills model of reading development. *Scientific Studies of Reading*, *11(1),* 3–32.

Vernazza-Martin, S., Martin, N., Vernazza, A., Lepellec-Muller, A., Rufo, M., Massion, J., & Assaiante, C. (2005). Goal directed locomotion and balance control in autistic children. *Journal of Autism and Developmental Disorders, 35(1),* 91–102.

Vivanti, G., & Hamilton, A. (2014). Imitation in autism spectrum disorders. *Handbook of Autism and Pervasive Developmental Disorders, Vol 1: Diagnosis, Development, and Brain Mechanisms*, 278–302.

Vivanti, G., Hamner, T., & Lee, N. R. (2018). Neurodevelopmental Disorders Affecting Sociability: Recent Research Advances and Future Directions in Autism Spectrum Disorder and Williams Syndrome. *Current Neurology and Neuroscience Reports, 18(12),* 94.

Volkmar, F. R., Lord, C., Bailey, A., Schultz, R. T., & Klin, A. (2004). Autism and pervasive developmental disorders. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *45(1),* 135–170.

Volman, M.J.M., Van Schendel, B.M., & Jongmans, M. (2006). Handwriting difficulties in primary school children: a search for underlying mechanisms . *American Journal of Occupational Therapy*, 60: 451 – 460.

Wang, Z., Magnon, G. C., White, S. P., Greene, R. K., Vaillancourt, D. E., & Mosconi, M. W. (2015). Individuals with autism spectrum disorder show abnormalities during initial and subsequent phases of precision gripping. *Journal of Neurophysiology, 113(7),* 1989–2001.

Wang, Z., Hallac, R. R., Conroy, K. C., White, S. P., Kane, A. A., Collinsworth, A. L., Sweeney, J. A., & Mosconi, M. W. (2016). Postural orientation and equilibrium processes associated with increased postural sway in autism spectrum disorder (ASD). *Journal of Neurodevelopmental Disorders, 8,* 43.

Wang X., & Cheng Z. (2020). Cross-sectional studies: Strengths, weaknesses, and recommendations. *Chest*, *158(1S),* pp. S65–S71.

Waterman, A. H., Havelka, J., Culmer, P. R., Hill, L. J. B., & Mon-Williams, M. (2014). The ontogeny of visual-motor memory and its importance in handwriting and reading:

A developing construct. *Proceedings of the Royal Society B: Biological Sciences, 282,* 20140896.

Watson, R. (2015). Quantitative research. *Nursing Standard (Royal College of Nursing (Great Britain): 1987), 29(31),* 44–48

Wechsler, D. (1999). *Wechsler Abbreviated Scale of Intelligence*. London, England: Harcourt Assessment.

Weiss, B. D., Hart, G., McGee, D. L., & D'Estelle, S. (1992). Health status of illiterate adults: relation between literacy and health status among persons with low literacy skills. *The Journal of the American Board of Family Practice*, *5(3),* 257–264.

Weiss, M. J., Moran, M. F., Parker, M. E., & Foley, J. T. (2013). Gait analysis of teenagers and young adults diagnosed with autism and severe verbal communication disorders. *Frontiers in Integrative Neuroscience, 7,* 33.

Wedyan, M., Al-Jumaily, A., & Crippa, A. (2019). Using machine learning to perform early diagnosis of Autism Spectrum Disorder based on simple upper limb movements. *International Journal of Hybrid Intelligent Systems, 15,* 195–206.

Wild, K. S., Poliakoff, E., Jerrison, A., & Gowen, E. (2012). Goal-directed and goalless imitation in autism spectrum disorder. *Journal of Autism and Developmental Disorders, 42(8),* 1739–1749.

Williams, J. H., Whiten, A., & Singh, T. (2004a). A systematic review of action imitation in autistic spectrum disorder. *Journal of Autism and Developmental Disorders*, *34(3),* 285–299.

Williams, J. H., Massaro, D. W., Peel, N. J., Bosseler, A., & Suddendorf, T. (2004b). Visual-auditory integration during speech imitation in autism. *Research in Developmental Disabilities*, *25*, 559–575.

Williams, J.G., Higgins, J.P., & Brayne, C.E. (2006). Systematic review of prevalence studies of autism spectrum disorders. *Archives of Disease in Childhood, 91,* 8–15.

Williams, B., Onsman, A., & Brown, T. (2010). Exploratory Factor Analysis A Five-Step Guide for Novices. *Australasian* Journal *of Paramedicine*, *8*, 1-13.

Wilson, M., & Knoblich, G. (2005). The Case for Motor Involvement in Perceiving Conspecifics. *Psychological Bulletin*, *131(3),* 460–473.

Wilson, R. B., McCracken, J. T., Rinehart, N. J., & Jeste, S. S. (2018). What's missing in autism spectrum disorder motor assessments? *Journal of Neurodevelopmental Disorders*, *10(1),* 33.

Wing, L., & Gould, J. (1979). Severe impairments of social interaction and associated abnormalities in children: Epidemiology and classification. *Journal of Autism and Developmental Disorders, 9(1),* 11-29.

Wing, L. (1997). The history of ideas on autism: Legends, myths and reality. *Autism* 1: 13-24

Wing, L., & Potter, D. (2002). The epidemiology of autistic spectrum disorders: is the prevalence rising?. *Mental Retardation and Developmental Disabilities Research Reviews, 8(3),* 151–161.

Witte, J.S., Greenland, S., Haile, R.W., & Bird, C.L. (1994). Hierarchical regression analysis applied to a study of multiple dietary exposures and breast cancer. *Epidemiology*. *15(6):*612-21.

Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering* (pp. 1-10).

Wolf, M.S., Wilson, E.A.H., Rapp, D.N., Waite, K.R., Bocchini, M.V., Davis, T.C.,& Rudd, R.E.(2009).Literacy and learning in healthcare. *Pediatrics*,*124*, S275 – S281 .

Wolpert, D.M. (1997). Computational approaches to motor control. *Trends in Cognitive Sciences 1:*209–16.

Wolpert, D.M. & Kawato,M. (1998). Multiple paired forward and inverse models for motor control. *Neural Networks 11(7–8):*1317–29.

Wolpert, D. M., & Flanagan, J. R. (2001). Motor prediction. *Current biology: CB, 11(18),* R729–R732.

Wolpert, D. M., Doya, K. & Kawato, M. (2003). A unifying computational framework for motor control and social interaction. *Philosophical Transactions of the Royal Society B: Biological Sciences 358*:593–602.

Wong, V. C. N. & Hui, S. L. H. (2007). 'Brief report: emerging services for children with ASD spectrum disorders in Hong Kong (1960–2004). *Journal of Autism Developmental Disorder, 38*, pp. 383–9.

Woodworth, R. S. (1899). Accuracy of voluntary movement. *The Psychological Review: Monograph Supplements, 3(3),* i–114.

Worringham, C. J. (1991). Variability effects on the internal structure of rapid aiming movements. *Journal of Motor Behaviour, 23*(1), 75–85.

Xavier, J., Gauthier, S., Cohen, D., Zahoui, M., Chetouani, M., Villa, F., Berthoz, A., & Anzalone, S. (2018). Interpersonal Synchronization, Motor Coordination, and Control Are Impaired During a Dynamic Imitation Task in Children With Autism Spectrum Disorder. *Frontiers in Psychology, 9*, 1467.

Yang, H. C., Lee, I. C., & Lee, I. C. (2014). Visual feedback and target size effects on reach-to-grasp tasks in children with autism. *Journal of Autism and Developmental Disorders, 44(12),* 3129–3139.

Zakaria, N.K., Tahir, N.M., & Jailani, R. (2020). ASD Children gait classification based on principal component analysis and linear discriminant analysis. *International Journal of Emerging Trends in Engineering Research, 8:*2438–45.

Zeidan, J. (2022). Global prevalence of autism: a systematic review update. *Autism Research. 15*, 778–790.

Ziviani, J., & Elkins, J. (1984). An Evaluation of Handwriting Performance. *Educational Review, 36(3),* 249–261.

Zhang, Z., Song, Y., & Qi, H. (2017).: Age progression/regression by conditional adversarial autoencoder. *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pp. 5810–5818

Zheng, R. (2015). *A comparison of constrained and unconstrained reaching movements by people with and without Autism. University of Manitoba Thesis. Available from: https://library-archives.canada.ca/eng/services/services-libraries/theses/Pages/item.aspx?idNumber=1356862310*

Zhao, H., Zheng, Z., Swanson, A., Weitlauf, A., Warren, Z., & Sarkar, N. (2018). Design of a Haptic-Gripper Virtual reality system (Hg) for analyzing fine motor behaviors in

children with autism. *ACM Transactions on Accessible Computing (TACCESS), 11(4),* 1–21.

Zheng, R., Naiman, I. D., Skultety, J., Passmore, S. R., Lyons, J., & Glazebrook, C. M. (2019). The Impact of Different Movement Types on Motor Planning and Execution in Individuals with Autism Spectrum Disorder. *Motor Control, 23(3),* 398-417*.*