SENSORIMOTOR PLANNING, INTEGRATION, AND EXECUTION PROCESSES IN AUTISM SPECTRUM DISORDERS

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Contents

I Thesis Abstract

The focus of this thematic thesis was to conduct an examination into the autistic differences to underlying sensorimotor planning, integration, and execution processes. The distinct protocols in the current programme of work: imitation in upper-limb motor control (chapter two), upper-limb single and two-segment manual aiming (chapter three) and stepping behaviour in obstacle crossing (chapter four), provide independent, yet related, examinations of underlying autistic sensorimotor behaviour compared to typically developing controls. Chapter two revealed that autistic participants successfully imitated atypical biological motion kinematics when the imitation environment was structured to facilitate trial-by-trial processing, and interference in the inter-trial delay over time influenced consolidatory offline sensorimotor processes related to planning. Chapter three revealed that autistic adolescents show significant alterations to sensorimotor planning processes during single and two-segment manual aiming. Chapter four revealed significant sensorimotor integration differences during obstacle crossing in autistic participants who require substantial or very substantial support. Across all experimental chapters in the current thesis, there also appeared to be significant autistic variability increases across several key dependant variables, implicating altered sensorimotor feedforward planning processes. Additionally, there also appears to be evidence of intact sensorimotor feedback processes whereby autistic participants utilise the online integration of sensory information to compensate for earlier variabilities. This thesis will seek to synthesise, summarise, and appraise key findings between experimental chapters, relative to current literature, with both theoretical and wider implications for the motor control and autistic communities discussed and future directions identified.

II Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

III Acknowledgements

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IV Table Legends

V Figure Legends

VI Abbreviations

Abbreviation	Long Form
ADOS	Autism Diagnostic Observation Schedule
APA	American Psychological Association
ASD	Autism Spectrum Disorders
CDC	Centre for Disease Control and Prevention
DSM	Diagnostic and Statistical Manual of Mental Disorders
M1	Primary Motor Cortex
MABC	Movement Assessment Battery for Children
PA	Peak Acceleration
PCM	Planning and Control Model
PD	Peak Deceleration
PPVT	Peabody Picture Vocabulary Scale
PTTPV	Percentage Time to Peak Velocity
PV	Peak Velocity
RRB	Restricted and Repetitive Behaviours
rTMS	repetitive Transcranial Magnetic Stimulation
SALT	Speech and Language Therapy
SCI	Social Communication and Interaction
SD	Standard Deviation
SEN	Special Educational Needs
SENCO	Special Educational Needs Co-ordinator
SP	Sensory Profile
SRC	Stimulus-Response Compatibility
SRS	Social Responsiveness Scale
STORM	Social Top-down Response Modulation
SV	Spatial Variability
TA	Teaching Assistant
TD	Typically Developing

1 Chapter One: Introduction

1.1 Prologue

The current thematic thesis aims to conduct an examination into the autistic differences to underlying sensorimotor planning, integration, and execution processes, across three independent experimental chapters. The empirical chapters are preceded by an introductory chapter reviewing and outlining current and relevant literature. They are then followed by an epilogue chapter where results from each experimental chapter will be presented, synthesised, and appraised, with theoretical and wider implications for the motor control and autistic communities discussed, and future directions recommended. This introductory chapter will provide a review of the key literature that form the basis for the rationale behind each experimental protocol, and the experimental manipulations made within them. The following subsections of this introductory review will seek to provide a coherent narrative to explain the contexts and motivations behind this programme of research.

1.2 Autism Spectrum Disorder

Autism spectrum disorder (ASD; henceforth autism) is a neurodevelopmental disorder principally 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). In 1943 Leo Kanner was one of the first to acknowledge and document autism in published work, providing an initial definition as "an autistic disturbance of affective contact". His seminal paper, containing a comprehensive case study of eleven children, recognised limited communicative language and a reduced interest in

social contact, with restricted and repetitive behaviours (Kanner, 1943). Kanner's work was followed up by Hans Asperger (1944) with his initial published depiction of autism – "autistic psychopathy in children", which showed children demonstrating differences in social interaction, both verbal and non-verbal communication, and specific and limited interests. The assessments and observations put forward in these seminal papers (Asperger, 1944; Kanner, 1943) are central to the way in which we view, understand, and diagnose autism at present (American Psychiatric Association, 2013; Harris, 2018).

History and Diagnosis

Following the seminal work of both Kanner (1943) and Asperger (1944) identifying the disorder we now define as autism, an epidemiological study of "early infantile autism" revealed an initial prevalence of ~4.5 per 10,000 (Lotter, 1966). Expanding the initial Kanner (1943) definition of autism, a larger group of children (~15 per 10,000 children) displayed difficulties with social interaction, communication, and imagination. This triad became known as the "triad of impairments" (Wing & Gould, 1979). The Diagnostic and Statistical Manual of Mental Disorders, a handbook used by health care professionals containing descriptions, symptoms, and distinguishing criteria for supporting the diagnosis of mental disorders, first introduced a classification of "early infantile autism" upon publication in 1980 to reflect the distinction made between autism and schizophrenia in 1971 (DSM-III; American Psychiatric Association, 1980; Kolvin, 1971). By the subsequent iteration of the DSM (DSM-IV), the term "Asperger syndrome" was proposed to distinguish "autistic disorder" diagnoses from individuals who demonstrate typical IQ and verbal communicative skills yet show difficulty with non-

verbal communication (American Psychiatric Association, 1994). In 2013, the DSM-V introduced a singular overarching diagnosis encompassing all subcategories: "autism spectrum disorder", and due to this, the term Asperger's syndrome was no longer considered as a separate condition. And as such, autism spectrum disorder is defined by two main diagnostic criteria: (1) impaired social communication and/or interaction, (2) restricted and/or repetitive behaviours (American Psychiatric Association, 2013). It is important to note that terminology and language is ever evolving, and current depictions of autistic individuals should strive to reflect contemporary cultural views, largely decided upon by the autistic community and their related networks. Current views no longer use terminology such as "higher- or lower-functioning" and instead, many involved with autistic individuals and their networks prefer to focus on a description of the need for support (e.g., requiring little, substantial, or very substantial support).

Prevalence

Worldwide median prevalence estimates have risen, and seem to continue to rise, an increase likely to be occurring due to a broadening of diagnostic criterion, a separation of diagnostic criteria from other developmental disabilities, and an increase in awareness of autism across both the lay public and professionals (Baio et al., 2018; Elsabbagh et al., 2012). Prevalence estimates suggest that in some US states, autism prevalence has increased from ~6.7 per 10,000 children in 2000 to ~16.8 per 10,000 in 2014 (Baio at al., 2018). The prevalence rates in the UK remained relatively stable throughout 2004-2010, with 38 cases per 10,000 in boys aged 8, and 8 cases per 10,000 in girls of the same age (Taylor et al., 2013), however, the preceding approximately 15-year period saw significant increases from 4 per 10,000 children in 1988 to 25 per

10,000 children in 2001 (Hagberg & Jick, 2010). More recently, UK autism prevalence estimates suggest 17.5 per 10,000 children have an autism diagnosis, with male pupils showing a prevalence of 28.1 per 10,000 and female pupils a prevalence of 6.5 per 10,000. Current estimates of the ratio of male-to-female cases appear close to the widely reported 4:1 at 4.32:1 (Roman-Urrestarazu et al., 2021).

Characteristics of Autism

Social Interaction

One of the principal diagnostic criteria of autism outlined in the DSM-V is differences in social interaction and communication (American Psychiatric Association (APA), 2013). Such differences include variations in social orienting, where an individual shows a failure to spontaneously orient their attention to available, naturally occurring social stimuli within one's environment (e.g., attending to having their name called) (Dawson et al., 1998). Another example includes a lack of social eye contact (e.g., failing to make appropriate eye contact during a social interaction) (Senju & Johnson, 2009). Failure to use appropriate eye contact is one observation documented throughout an Autism Diagnostic Observation Schedule (ADOS-2) assessment, which is one part of the multitude of tools used to make a diagnostic assessment (Lord et al., 2012). Observable and measurable differences in social orienting and joint attention successfully distinguish autistic and typically developing 3- to 4-year-old children (Dawson et al., 2004), with autistic children demonstrating differences in both the initiation of, and response to, indicating behaviours during play (Mundy et al., 1986). These indicating behaviours involve the modulation of eye contact in a social manner to share attention to a common referent. Coordination of attention to a common referent (Mundy, 2018) and following the referential gaze of

another person (Vivanti et al., 2017), are documented areas in which autistic individuals show difficulty. These clear social interaction differences may well have significant quality of life implications for autistic individuals both in early life and throughout development, such as difficulties forming and maintaining relationships with peers (e.g., making friends), and finding suitable employment (Burgess & Gutstein, 2007; Chiang et al., 2013).

Communication

Language development, and the ability to use developed language as a tool for communication are important when understanding how autism presents. Parents of to-be-diagnosed autistic children may first become concerned about their child's development due to early delays or regressions in speech development. These identifiable factors can be used to differentiate autism from other neurodevelopmental disorders (Tager-Flusberg et al., 2005). Disruptions to a typical developmental trajectory of communication may be present in autistic children as early as twelve months of age and may manifest as a desynchronisation of vocal patterns with the parent or caregiver, delayed onset of 'babbling', and a lack of responsiveness to the communicative efforts of others (Landa, 2007). Following these early manifestations and disruptions to early communicative speech, during the next 12-48 months, the development of communication in autism is described as reduced in frequency and diversity (Landa, 2007; Wetherby et al., 2004). The ability to communicate is not solely reliant on the ability to speak or make utterances or 'babbles', non-verbal methods (e.g., waving, pointing, etc.) can also be highly efficient and effective, and are suggested to play a prominent role in communication (Duncan, 1969). Differences in the use of gesture and non-verbal communicative methods has been known to

differentiate autistic and non-autistic children for some time (Mundy et al., 1986), with autistic children using fewer gestures at both 12 and 18 months of age (Mitchell et al., 2006).

Co-speech Gestures

Simultaneous presentation of both speech and gesture can enhance understanding, learning, transfer, and retention of information (Congdon et al., 2017). However, autism specific processing patterns seem to occur when co-speech gestures accompany verbal speech (Silverman et al., 2010). For example, typically developing children more quickly identify the correct label for a depicted object when co-speech gestures accompany verbal speech, whereas autistic children display significantly slowed identification of, and fixation to, a target when co-speech gestures were implemented (Silverman et al., 2010). Gestural differences in autism are widely reported. For example, between 9 to 12 months of age autistic children are less likely to use joint attention gestures, and between 15 to 18 months of age are less likely to use both joint attention and social interaction gestures (Watson et al., 2013). Autistic children also show difficulty producing gestures either by imitation, with tools or objects, and to produce commands, compared to typically developing children (Dziuk et al., 2007). Gesture production is a reliable predictor of early communication skills related to the development of both verbal and non-verbal communicative ability in autism (Ramos-Cabo et al., 2019). These autistic differences might be related to an autistic specificity in the use of communicative gestures during development (Sowden et al., 2013), and the demanding nature of filtering social-motor noise during social interactions (Wang & Hamilton, 2012).

Restricted and Repetitive Behaviours

Restricted and repetitive behaviours (henceforth RRBs) are a prominent feature of autism that can constitute a major barrier to learning and social development (Leekam et al., 2011). 'RRBs' as an overarching term fails to capture the diversity of these behaviours and as such, due to their wide variety, less appears to be known about their development, trajectory and aetiology (Harrop et al., 2014). Attempts to categorise RRBs, using subcategories such as those used in the Repetitive Behaviour Scale (RBS), help to provide consistency to the definitions of these behaviours. The aforementioned subcategories are defined as: ritualistic (e.g., insistence on following a rigid routine), stereotypic (e.g., hand flapping), self-injurious (e.g., banging of head), compulsive (e.g., displaying Obsessive Compulsive Disorder features), and restricted interests (e.g., a preoccupation with a specific topic) (Lam & Aman, 2007). Autistic children elicit both a higher frequency and greater diversity of these behaviours, although upon comparison, some behaviours were not unique to ASD and were also displayed by typically developing peers, albeit lesser in quantity (Harrop et al., 2014).

Theory of Mind

The basis of the theory of mind hypothesis is drawn from an examination of mentalising ability in autism (see meta-analysis by Chung et al., 2014). Mentalising refers to the ability to infer the mental states of others and has been documented to elicit difficulty for autistic individuals (Jolliffe & Baron-Cohen, 1999). Notably, autistic individuals perform typically on non-mentalistic control tasks, yet both autistic children and adults perform less well on a task designed to assess advanced mentalising ability (Happé, 1994; White et al., 2009). Theory of mind is the term used to represent the ability to understand that both we and others possess separate

independent mental states, and the ability to attribute mental states to others based on our own understanding of their lived experience (Wellman et al., 2001; Wimmer & Perner, 1983). The ability to make inferences regarding the desires, beliefs and emotions of others is suggested to be different in autism (Premack & Woodruff, 1978), and this belief forms the core of the theory of mind hypothesis (Baron-Cohen, 1989). A commonly used task to examine theory of mind is the Sally-Anne task (see Figure 1.1), a false-belief test in which only 20% of autistic participants can successfully pass, compared to 85% of typically developing participants and 86% of participants with Down's Syndrome (Baron-Cohen et al., 1985). The Sally-Anne task involves the participants hearing a story about two dolls, Sally who has a basket and Anne who has a box. The story begins with Sally placing a ball in her basket and then leaving the room. While Sally is not present, Anne removes the ball from the basket and places it into her box. Sally returns to the room to look for her ball. Participants are asked where Sally will look. The correct answer being that she will look in the location where she placed the ball, inside the basket. However, autistic individuals fail this false-belief test more often than typically developing individuals and indicate that Sally will look for the ball in the box where Anne moved it to (without Sally's knowledge). This test provides a mechanism to assess whether a participant will consider Sally's false belief by taking her perspective.

It has been suggested that altered cognitive processes, such as theory of mind, may, in part, contribute to the prominent behavioural differences seen in autism (Happé, Ronald, & Plomin, 2006). An examination of the cognitive ability of 100 autistic adolescents, across 10 independent tasks, revealed that theory of mind ability was associated with both social communication and the expression of RRBs (Jones et al., 2018). It may be the case that cognitive performance across both motor and social

domains develop in a related manner and are not solely independent of one another (Kenny et al., 2016).

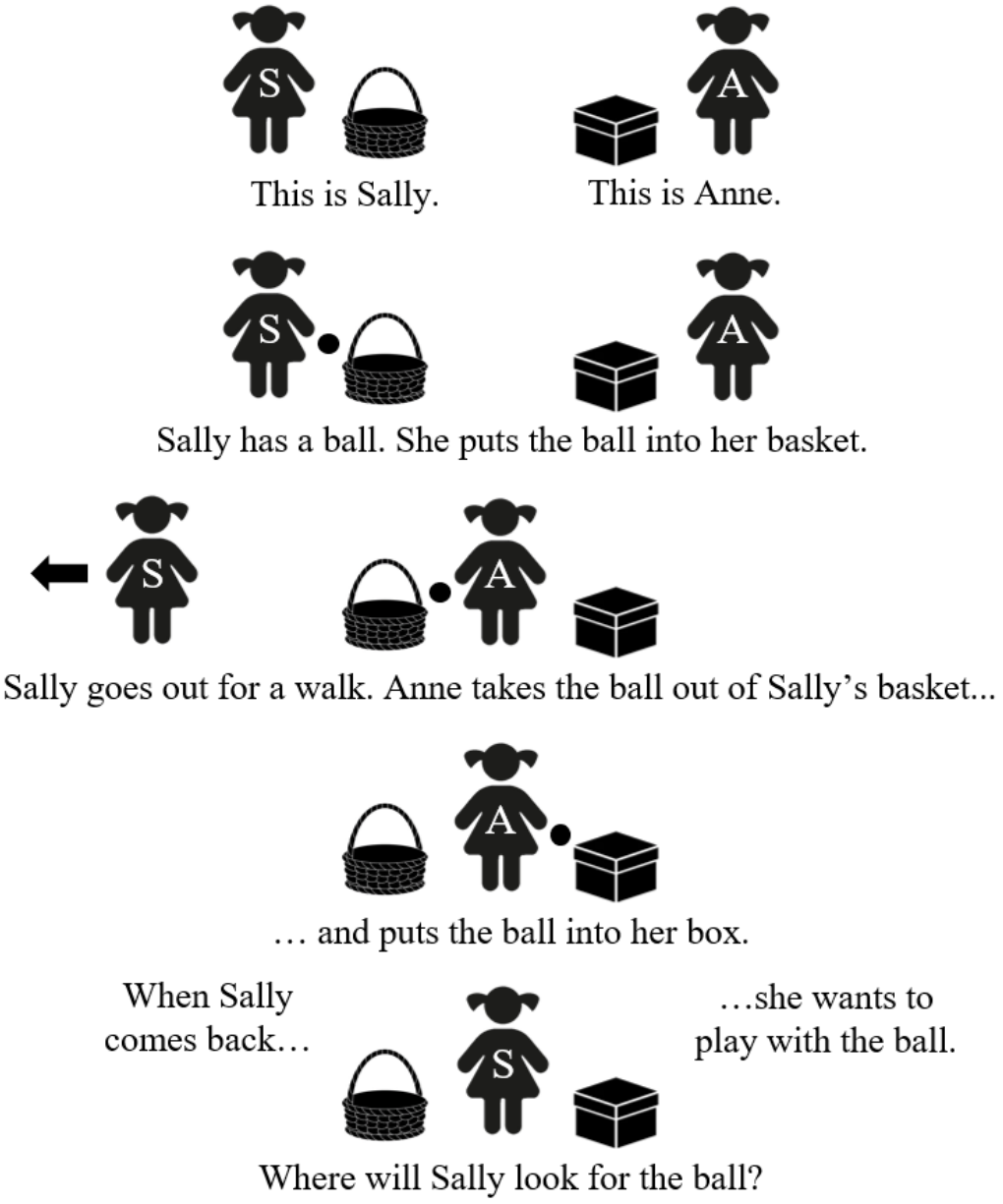

Figure 1.1: Schematic representation of the Sally-Anne task.

1.3 Sensorimotor Control Processes

Autistic individuals show clear differences to sensorimotor control processes that distinguish them from non-autistic individuals (Cavallo et al., 2021; Fournier et al., 2010a; Green et al., 2009; Jansiewicz et al., 2006; Kaur et al., 2018; Mari et al., 2003; Marko et al., 2015; Mostofsky & Ewen, 2011). Early accounts suggest that autistic children show objective, observable movement differences, such as delays to the onset of significant motor milestones (e.g., lying, righting, sitting, and crawling) during autistic development (Teitelbaum et al., 1998). Further research revealed that autistic children display frequent motor difficulty across a standardised assessment of gross and fine motor ability (MABC-2), with 79% of the experimental sample displaying observable and quantitative impairment (Green et al., 2009). A widely cited meta-analysis of motor differences in autism also found pronounced pervasive motor difficulties, indicating a lack of coordination and limited motor capability, in comparison to controls (Fournier et al., 2010a). Moreover, autistic children between 5 and 12 years of age demonstrate lower gross and fine motor performance, lower rates of movement, greater movement variability, and weaker interpersonal synchrony when compared to typically developing peers (Kaur et al., 2018). These well documented sensorimotor differences, however, are not yet formally classified as one of the core components of autism (as per the DSM-V) but are likely contribute to the altered development of social behaviours, such as the coordination of eye contact with speech and gesture, and the interpretation of the behaviour of others (Hannant et al., 2016a).

A Computational Approach

A computational model can be used to better understand and explain the implicated underlying sensorimotor processes, and the likely mechanisms recruited, leading to and during motor execution of a given action (see Figure 1.2). Within the context of an everyday task, such as reaching to pick up a cup of coffee, one must initially use their sensory systems (1) to gather crucial visual and proprioceptive information pertaining to the upcoming task. Any information gathered will be unified to create an estimation of one's current state (2) specifying the location of the cup, including its size and shape, where one's hand is located in space, and any other information deemed relevant to the task (e.g., any obstacles). Once the state estimation has been made, this estimation is compared to the desired state (e.g., "my hand is by my side, but I would like my hand to grip the handle of the cup to take a drink of coffee"). The sensorimotor system is then required to create a series of motor commands, via sensorimotor planning processes (3), to achieve the desired state as efficiently as possible (e.g., lift the arm, accelerate the arm towards the cup, open grip to appropriate aperture, decelerate the arm as to not collide with the cup and spill the coffee, grasp the cup). Planning processes are often described as the 'inverse model' as the process requires solving the problem of converting desired goals (e.g., taking a drink of coffee) into a suitable and effective sequence of motor commands to achieve the goal. Once created, the sequence of motor commands can be sent to the relevant musculature to initiate movement (5). However, errors can sometimes occur during execution for several reasons, such as interference or perturbation in the system, or errors during planning. Prior to movement initiation the sensorimotor system creates a copy of the to-be-executed motor commands (i.e., efference copy) and uses this copy to produce a feedforward prediction (4) of expected sensory inputs likely to occur

should the system follow the planned motor commands. This feedforward predictive model is required to correct for early errors in execution because actual sensory feedback gained via sensorimotor integration is relatively slow (approximately 165ms) to detect errors and inform corrections, which does not facilitate swift and efficient early corrections during the initial stages of execution (Young & Zelaznik, 1992). As the movement progresses, and actual sensory feedback becomes increasingly more available, afferent (i.e., sensory consequences) and efferent (i.e., motor commands sent to relevant musculature) signals are continually compared to inform ongoing alterations to the movement trajectory until and beyond movement termination.

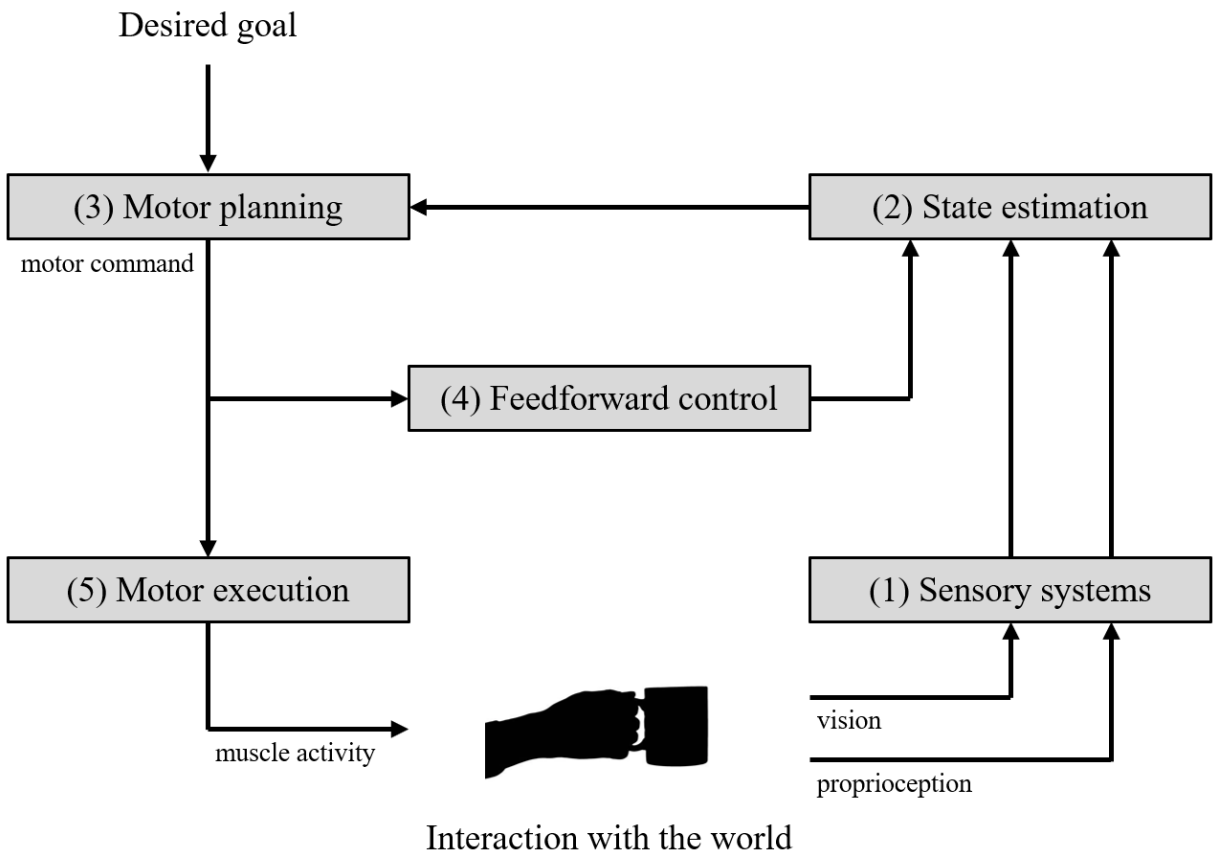

Figure 1.2: Schematic representation of the computational model depicting underlying sensorimotor control processes (adapted from Gowen & Hamilton, 2013).

The following subsections will seek to elaborate on the crucial sensorimotor processes (sensory systems, state estimation, motor planning, feedforward control, motor execution) and how these processes may be implicated in altered autistic sensorimotor control. Although described in a sequential manner, the sensorimotor control stages depicted by the computational model are by no means independent and distinct. As such, an individual may need to continually navigate the model and integrate sensory information from multiple sources (e.g., vision and proprioception) to inform alterations to the ongoing movement as changes to circumstances or contexts become more apparent, as more information becomes available.

(1) Sensory Systems

To execute motor actions precisely and accurately one must rely on their sensory systems to effectively process sensory stimuli, which informs feedforward predictions and the creation of motor commands to achieve a desired goal. Differences to the way in which sensory stimuli is processed or interpreted by internal sensory systems can heavily influence both the to-be-executed movement, and the continual refinement as the movement trajectory progresses. A common way to examine sensory processing in autism involves completion of a questionnaire, such as the validated and widely cited Sensory Profile (Ermer & Dunn, 1998). Data collected in this way can be a valuable mechanism to capture sensory processing disruptions in individuals who require substantial support, as there are several versions (e.g., teacher-report, caregiver-report etc.) each with slightly different scoring systems, facilitating adherence in underrepresented populations. In autism, clear sensory processing differences are reported across several modalities (notably auditory, visual, touch, and oral), with autistic individuals displaying significant disruptions compared to typically

developing peers (Kern et al., 2006). The prevalence of such disruptions is profound in autism, with some published work citing upwards of 95% of the experimental sample of 281 autistic children aged between 3-6 years demonstrating significant sensory processing disruptions compared to other typically developing children (Tomchek & Dunn, 2007). Although much of the research base has focused on sensory processing in autistic children, as one may expect there are also profound disruptions to sensory processing in adulthood. As above, almost 95% of the autistic adults included in the experimental sample experienced "extreme levels of sensory processing" (Crane et al., 2009).

In the context of movement execution, fundamental autism-specific differences in the sensitivity of tactile, movement or proprioceptive, auditory, and visual processing (Tomchek et al., 2014) may influence the processing efficacy of crucial stimuli pertaining to an upcoming movement (1), and in turn the subsequent sensorimotor control processes (2), (3), (4), and (5). More specifically, when executing actions both with and without vision, both autistic and typically developing children take longer to execute actions when vision is available, with the increase between no-vision and vision conditions being significantly larger for autistic individuals (Glazebrook et al., 2006). This finding indicates that both groups do successfully recruit both visual and proprioceptive systems. Although, the autism group may have experienced disruptions in the integration of the multiple available streams of information (e.g., proprioceptive, and visual) when vision accompanied proprioception, leading to considerable increases in movement time where greater sensorimotor integration is required. Autistic differences to the integration of visual information also occurred in point-to-point movement tasks whereby the presence of a visual distractor yielded little impact on planning and execution processes, in

contrast to typically developing children (Dowd et al., 2012). It is suggested that autistic children were not successfully perceiving and integrating all available environmental cues (e.g., the visual distractor), which if processed and integrated successfully, would likely modulate the upcoming movement. Further research suggests that specific differences in sensorimotor integration may be due to an autistic specificity in the prioritisation of proprioceptive, over visual, information (Haswell et al., 2009). During a motor learning experiment participants were required to manipulate a robotic arm that produced differing velocity-dependent curl force fields which perturbed motion. Patterns of generalisation in the autism group revealed a stronger than typical reliance on proprioception (Haswell et al., 2009), which implicated altered sensorimotor processing and integration of visual information in autism compared to typically developing peers.

(2) State Estimation

To successfully create and recruit a motor plan for an upcoming action, the sensorimotor system requires a state estimation to be made. This estimation contains pertinent information regarding one's immediate environment and one's relative location within that environment, in relation to specific targets or objects to be manipulated. Also of importance are specific details regarding weight, speed, or direction of the target or object. Multisensory processing, by the sensory systems (1) contained in the sensorimotor system, provide in-depth information (i.e., visual, and proprioceptive) to support the creation of a state estimation that is as accurate as possible (Gowen & Hamilton, 2013; Molinari et al., 2009), to inform and facilitate accurate motor planning (3). Multisensory integration has been reported to be different in autism when compared to typically developing children (Stevenson et al., 2014;

Kawakami et al., 2020). A task designed to assess multisensory integration, namely the sound-induced flash illusion task, displayed a combination of visual stimuli (a singular flash) accompanied by varying quantities of auditory stimuli (a series of 2-4 beeps) to typically developing and autistic children. Typically developing children generally report the perception of multiple flashes, despite only a singular flash being presented, indicating a likely cross-over across sensory modalities during sensorimotor integration. On the other hand, autistic children are much less likely to report the illusory effect, potentially implicating differences to sensorimotor integrative processes that require combination of multiple sensory inputs (Stevenson et al., 2014; Kawakami et al., 2020). Additional examinations using illusions of this type have also provided valuable insight into the potential of an autism-specific difference to the window in which multisensory information is processed. More specifically, by adapting the latency between presentation of stimuli, it is evident that altered multisensory processing in autism resulted in a window of 600ms to yield an illusory effect, compared to 300ms for controls (Foss-Feig et al., 2010; Kwakye et al., 2011). These findings indicate that the successful processing of multiple sensory streams in autism is indeed possible, albeit for that processing to be successful a greater temporal window is required. In a relatively fast-paced movement, such as reaching to pick up a cup of coffee, a doubling of processing time due to altered integration may impact the efficacy and accuracy of state estimations, therefore impacting upon the probability of smooth and efficient movement execution.

(3) Motor Planning

Using the generated state estimation and the desired goal, a sequence of motor actions is formulated into a motor plan to achieve the to-be-executed movement

efficiently and effectively. In the context of the desired goal being to reach and grasp a cup of coffee, one would utilise the formulated state estimation (e.g., a snapshot of the environment and one's location within it) to inform the force production and pattern of motor actions to direct the hand to the handle of the cup (Wolpert 1997). The specific forces and sequence of actions (e.g., flexion or extension of the elbow joint) needed to accelerate and decelerate the limb in a swift yet controlled manner, whilst also providing the most comfortable posture at the target location (e.g., hand holding the cup appropriately), are determined by retrieval of previous actions that may be similar from one's sensorimotor repertoire (Rosenbaum et al., 1992). Motor planning is not solely an isolated event performed before initiation, the motor plan can be continually refined and updated to control action online, correcting for any emerging errors by adapting the movement trajectory as it progresses.

It has been reported that autistic children and adults exhibit altered sensorimotor planning processes, identified primarily through examinations of reaction time (Glazebrook et al., 2006, 2008; Mari et al., 2003; Rinehart et al., 2001). More specifically, when young adults performed manual aiming actions to different targets (i.e., button presses), autistic participants were both slower to initiate (longer reaction times) and execute (longer movement times) than their typically developing peers (Glazebrook et al., 2009). There is also evidence to support that autistic children do not plan sequential motor tasks (e.g., several actions linked in sequence, such as a reach and place task) in the same way as typically developing children (Fabbri-Destro et al., 2009). For example, when required to pick up and place an object into a container, typically developing children performed elongated movement times in the reach, and place, phases when additional precision is required (i.e., placing into a smaller container) to complete the motor task more accurately. Autistic children,

however, do not modulate the timing of the reach phase based on the difficulty of the subsequent phase, and only modulate timing of the place phase according to the container size. It appears to be the case that autistic children may approach sequential actions as independent actions, opposed to typically developing children who alter multiple segments of a sequential action based upon planned expectations of other upcoming segments. Kinematic analysis of various upper-limb motor control tasks show that autistic individuals exhibit more temporal and spatial variability over the initial phase of movement (Foster et al., 2020a; Glazebrook et al., 2006), which may be related to difficulty in the accurate specification of forces needed for movement execution during the formation of a motor plan (Wolpert et al., 1995). Force patterns of autistic children can also successfully distinguish them from neurotypical peers. Notably, on handheld touch-sensitive tablet tasks, autistic children use a greater force at screen contact with an altered distribution of force during gesture (Anzulewicz et al., 2016), implicating further autism specific differences to feedforward planning processes related to the accurate specification of musculature force (Mosconi et al., 2015; Wang et al., 2015; Wolpert et al., 1995). If a motor plan is created that inherently contains unspecified or inaccurate details pertaining to the forces required, it may result in significant increases in variability when the planned movement is executed as online error corrections and alterations become more regularly required.

(4) Feedforward Control

During early stages of movement, execution is primarily driven by the efficacy of the motor plan and predictions made about changes to one's state as the plan progresses. One can use a copy of this motor plan (i.e., efference copy) to predict the sensory consequences (i.e., predicted afferent signals) prior to actual sensory feedback

(i.e., actual afference) becoming available, as sensory feedback cannot be integrated into the sensorimotor system to inform action quickly enough to influence early execution (Elliott et al., 2010, 2017). This predictive, feedforward process allows comparisons between the actual efferent signals (sent to relevant musculature) and the expected efferent signals (predictions made by feedforward control processes), with any discrepancies facilitating early error correction before actual sensory feedback can be utilised (Von Holst, 1954; Elliott et al., 2010; Miall & Wolpert, 1996; Wolpert & Flanagan, 2001). These comparisons can allow adjustments or alterations to be made regarding acceleration or deceleration of the limb (e.g., the hand approaching the cup of coffee) in the initial stages of execution, typically occurring between movement initiation and peak acceleration (Elliott et al., 2010).

Manual loading (Schmitz et al., 2003) and grip force production tasks (David et al., 2009; Mosconi et al., 2015; Wang et al., 2015) suggest autistic differences to feedforward control driven predictive processes. For example, in a grip force task requiring participants to generate a target force by squeezing the thumb and index finger onto opposing load cells, autistic individuals produced less accurate initial force contractions than controls (Mosconi et al., 2015). The less accurate initial forces were accompanied by greater peak force rates and larger overshoots. Autistic individuals also seemed to show greater variability when striving to sustain a specific force, with an increased reliance on slower feedback-based mechanisms, compared to faster feedforward predictive mechanisms (David et al., 2009; Mosconi et al., 2015). An apparent autistic preference for feedback over feedforward motor control processes may indicate that the autistic sensorimotor system is attempting to adapt the movement trajectory, correcting for early variabilities during motor execution, by integrating and utilising available sources of sensory information when they become available (e.g.,

vision and/or proprioception) (Desmurget & Grafton, 2000; Elliott et al., 2010). And it may be the case that the autistic sensorimotor system is utilising feedback mechanisms to compensate for altered planning processes which elicit a difficulty in specifying the required forces for accurate early movement execution (Elliott et al., 2010; Mosconi et al., 2015; Wang et al., 2015).

(5) Motor Execution

As a movement progresses along its trajectory, there becomes increasing opportunity for further comparison between expected and perceived efference (i.e., motor signals) and afference (i.e., the sensory consequences of the performed movement). This sensory information (e.g., visual, and proprioceptive) can be utilised (if available) to inform and refine the internal action model of the specific movement being performed (Elliott et al., 2010, 2017). Regulation of the limb during execution is informed by frequently updating stored representations, containing efferent and afferent information, based upon the conclusions made during comparisons until and beyond movement termination. If the integration of available sensory information results in a discrepancy from the expected signals during execution, online adaptations to the movement trajectory can be made to attempt to correct for altered planning processes or any perturbations experienced. After movement termination, a processing period allows the sensorimotor system to refine the internal action model based on the newly attained efferent and afferent information acquired on trial *N*, which can be used to update the sensorimotor representation and aid in the planning of trial *N+1* (Elliott et al., 2010, 2017; Wolpert et al., 2011). As we progress through life, the sensorimotor representations (i.e., internal action models) of actions that we perform (e.g., reaching to pick up a cup of coffee) will be continually refined both throughout, and following,

execution. As a result, we can utilise stored representations to facilitate performance of both identical and similar actions (e.g., we can use a stored representation of reaching to pick up a cup to reach successfully and efficiently to pick up another object, such as a glass), even if the upcoming movement is novel and has not been performed before. The sensorimotor system will seek to recruit and utilise relevant stored internal action models to assist performance of novel tasks. If the recruited internal action model is not sufficient, further refinement via both online and offline sensorimotor processes will occur to facilitate successful execution in future performance of the specific action.

As mentioned in an above section (3), an autism specific increase in spatial variability at peak acceleration indicates less effective motor planning, however, variability reductions across the movement trajectory (i.e., at other kinematic markers such as peak velocity, peak deceleration or movement endpoint), indicate that available sensory information (e.g., vision and/or proprioception) is processed to make successful online corrections during movement execution (Foster et al., 2020a; Glazebrook et al., 2006). Throughout sustained force contraction tasks, autistic individuals also show an increased reliance on these slower, integrative feedback mechanisms that occur as the movement progresses (Mosconi et al., 2015), opposed to feedforward predictive planning processes. Feedback-based movement corrections indicate operational sensorimotor adaptation across repeated trials leading to the within-trial, and between trial (inter-trial interval), refinement of a developing internal action model (Haswell et al., 2009; Elliott et al., 2010, 2017; Mostofsky & Ewen, 2011).

Dorsal and Ventral Visual Streams

As discussed, the sensorimotor control of everyday actions relies upon successful integration and processing of sensory information, particularly visual information (Berthier et al., 1996; Saunders et al., 2003). The visual system is suggested to be hierarchically organised into two streams: one responsible for constructing a perceptual representation of our world and the objects within it (ventral stream), and another responsible for visual guiding of actions within that representation (dorsal stream) (see Figure 1.3) (Goodale & Milner, 1992; Milner & Goodale, 2008). These visual streams appear structurally independent, with the ventral stream projecting visual information to inferotemporal cortex and the dorsal stream projecting visual information to posterior parietal cortex (Goodale & Milner, 1992; Goodale & Westwood, 2004). Notably however, the ventral and dorsal visual streams are not viewed as completely functionally independent, and instead work together in a complementary manner to utilise visual input to control our complex, everyday behaviour (Goodale & Westwood, 2004). Importantly, it appears that the ventral stream provides the perceptual foundation to identify objects, make predictions and facilitate the offline control of action by forecasting future actions and utilising stored representations to plan effectively. Conversely, the dorsal stream utilises moment-to-moment information to generate and control skilled actions (Goodale, 2011). Using the picking up a cup of coffee example outlined above, the ventral stream primarily allows us to identify that the object in front of us is indeed a cup, and the dorsal stream allows us to modulate and control our actions as we reach through space to grasp and pick it up. Both streams work in tandem with one another to produce the adaptive behaviours we perform in everyday life (Goodale, 2011; Goodale & Humphrey, 1998).

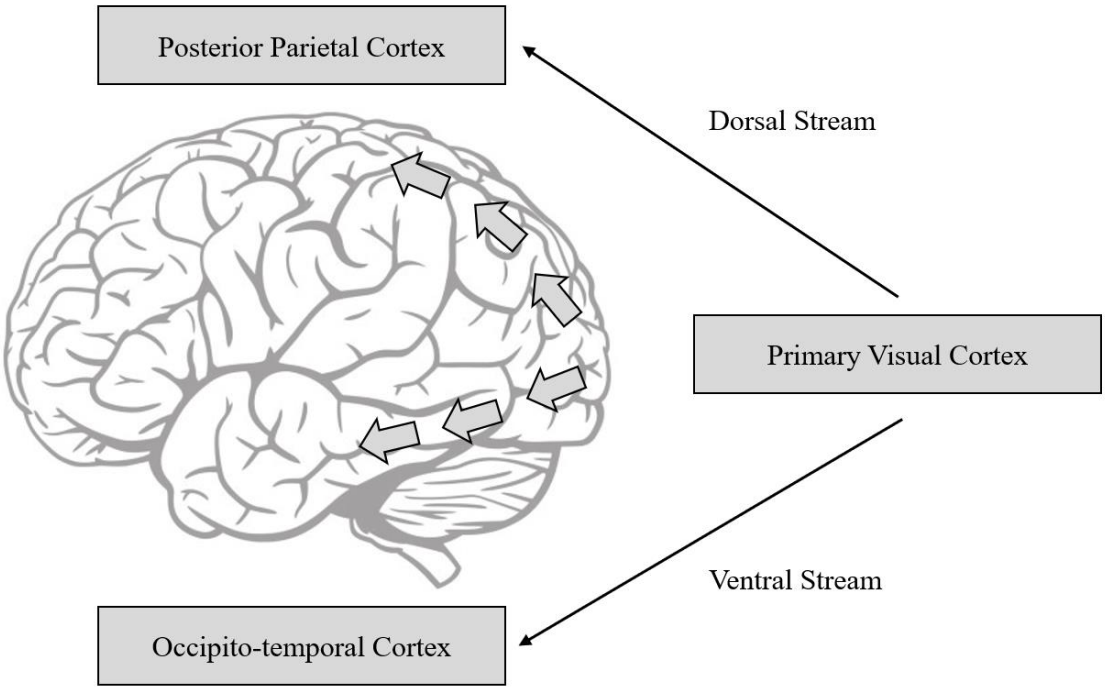

Figure 1.3: Schematic representation of the ventral and dorsal visual streams (adapted from Goodale & Westwood, 2004).

Impact of Sensorimotor Processes on Social Development

Differences to underlying sensorimotor processes may well be a potential contributory mechanism underpinning the altered social development documented in autism, which forms the basis of the autistic diagnostic criteria (American Psychiatric Association (APA), 2013; Happé, Cook & Bird, 2017). Some sensorimotor skills, such as informational gestures, are a means of (e.g., wave, high-five), and/or facilitate (e.g., pointing to an object), social communication and interaction between people (Mandal, 2014). Typically, co-speech gestures, or meaningful gestures that accompany verbal speech, are described as being transitive or intransitive. Meaningful gestures that are transitive imply the use of an object (e.g., writing with a pen), whereas intransitive gestures do not (e.g., wave, high-five) (Balconi et al., 2015; Balconi et al., 2017).

Autistic children demonstrate greater performance when imitating known gestures compared with novel gestures (Carmo et al., 2013; Dziuk et al., 2007), but show difficulty producing gestures either by imitation (e.g., transitive and intransitive), with tools or objects (e.g., transitive), and to produce commands (e.g., intransitive), compared to typically developing children (Dziuk et al., 2007). Differences in the use, quality, and quantity of gestures (Mitchell et al., 2006; Dawson et al., 1998), may impact on quality of life and functional social development in autism (Cook, 2016; Nebel et al., 2016), by altering the coordination of eye contact with speech and gesture, and the interpretation of the behaviour of others (Hannant et al., 2016a). A key focus of current autism research, and funding, is to examine the scope of 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). With social interaction, communication and cognition differences being widely reported for the best part of a quarter of a century (Baron-Cohen et al., 1985; Happé & Frith, 1996) in autism, research is beginning to examine motor differences as a potential way to help support diagnosis and to provide evidence-based interventions to parents, schools, and specialist support networks (Harris, 2017; Li et al., 2017).

1.4 Imitation of Biological Motion

Imitation, at its core, is a profoundly social process that is fundamental to human cognitive, social, and cultural development (Over, 2020), and one that has been recorded to be acquired very early in life (Carpenter et al., 1998). Humans typically possess an innate ability to infer the goals and intentions of a demonstrator's actions

(namely imitation), to facilitate the recreation of both movement form and endpoint, purely via observation (Carpenter, 2006). The ability to represent the cardinal features associated with an observed movement is paramount to learning and executing novel actions performed by others (Hayes et al., 2016; Heyes, 2001). This mechanism ultimately depends primarily on the sensorimotor representations created and refined through both observed and performed repetitions of novel actions (Heyes, 2001). Imitation is not only used to learn novel actions in isolation, but it also underpins the development of social cognition (Rogers et al., 2010), interpersonal closeness and rapport (Chartrand & Bargh, 1999; Lakin & Chartrand, 2003), and in turn greatly facilitates cultural development (Over, 2020).

Extensive research has been conducted to assess the imitative ability of autistic individuals in comparison with those typically developing, due to the clear diagnostic criteria that favour social interaction and communicative differences (American Psychiatric Association (APA), 2013). An early examination of autistic imitative ability revealed a significantly greater imitation accuracy for the imitation of motor-object use (e.g., the demonstrator's use of an object), than bodily imitation (e.g., imitation of the demonstrator's body actions) (DeMyer et al., 1972). Consistent findings also occurred in a task created to assess voluntary imitation of non-symbolic actions (e.g., strumming a stick over a pipe rack harshly, or gently, to produce a loud or quieter sound), with autistic individuals showing difficulty with imitating the form used by a demonstrator, but not the end goal (Hobson & Lee, 1999). It appears to be the case that the functional connectivity between visual and motor processes is disrupted, or at the very least operating differently, during voluntary imitation in autism (Nebel et al., 2016). For example, Functional Magnetic Resonance Imaging (FMRI) of 50 autistic children (ages between 8 and 12 years old) showed that visual

and motor systems appear to be asynchronous, indicating a temporal incongruence between processes (Nebel et al., 2016). A significant processing timing difference is likely to greatly disrupt crucial sensorimotor integrative processes that assist both the feedforward planning and feedback control of actions, and therefore may underpin autistic sensorimotor differences that contribute to the altered functional social development in autism (Cook, 2016; Nebel et al., 2016). Previous work has sought to provide insight into the potential underlying processes and mechanisms that could influence sensorimotor integration, and imitative ability, in autism (Foster et al., 2020b; Hayes et al., 2016). Specifically, on a touch-sensitive tablet task utilising a stylus, autistic adults successfully and accurately imitated the biological motion kinematics of a presented model exhibiting a typical movement profile (e.g., depicting an acceleration profile akin to everyday movement), but encountered difficulty when attempting to imitate a model exhibiting an atypical movement profile (e.g., depicting an acceleration profile not likely to be familiar; Hayes et al., 2016). It was suggested that because the typical movement profile was likely to have been represented in the autistic sensorimotor repertoire of stored actions (or an action closely related that could be recruited and adapted), due to the similarity in profile to many everyday actions, imitation in this condition was facilitated. And additionally, imitation when an atypical movement profile was presented was not facilitated due to its inconsistency with likely stored representations. Follow-up research using a similar methodology, however, concluded that autistic individuals could imitate biological motion kinematics of both typical and atypical models, when the imitation environment was conducive to facilitate this imitation (Foster et al., 2020b). To clarify, when the trial structure was contained in a repeated and predictable blocked manner (opposed to the random trial orders seen in Hayes et al., 2016), autistic individuals could successfully

imitate both typical and atypical movement profiles. It is likely that the blocked practice structure facilitated imitation by providing a consistent opportunity, over numerous trials, to reinforce and refine sensorimotor representations of novel actions.

1.5 Sensorimotor Planning in Manual Aiming

Manual aiming actions are primarily guided by sequences of upper-limb actions towards, or to achieve, a specific target or goal. Goal-directed manual aiming tasks allow an in-depth examination of the underlying sensorimotor processes that underpin effective and efficient motor execution. In 1899, a seminal model illustrating the speed-accuracy relations of upper-limb actions was published (Woodworth, 1899). This model depicted upper-limb manual aiming actions as containing a ballistic (e.g., initial phase to move the limb closer to the target), followed by a homing (e.g., utilisation of vision and proprioception to adjust trajectory on approach to the target) phase. The relatively simple two-component model presented by Woodworth (1899) was iterated and developed over the next century, resulting in a multiple process model of limb control that outlines several key processes that underpin both feedforward planning and online control of goal-directed actions (Elliott et al., 2010). By utilising the multiple process model, one can evaluate the underlying sensorimotor processes involved in goal-directed manual aiming by assessing changes or alterations at specific kinematic markers (e.g., peak acceleration, peak velocity, peak deceleration, and movement endpoint) and inferring the way implicit processing events occur across the temporal period of a manual aiming trial (Elliott et al., 2010). Complementary models of planning and control, namely the planning and control model (PCM), indicate the differences between representations processed for motor planning and motor control

made by the sensorimotor system (Thomaschke et al., 2012). More specifically, the PCM posits that motor planning primarily utilises categorical representations (e.g., features of an action), whereas motor control primarily utilises spatial representations (e.g., where an object is in space) (Glover, 2004; Thomaschke et al., 2012). The purpose of motor planning is to integrate as much relevant information as possible to achieve the desired state (goal) as efficiently as possible, by creating or utilising and refining a stored motor plan (Miall & Wolpert, 1996). According to the PCM, motor planning processes bind and stabilise all relevant features of an upcoming action and inhibit access to the motor plan by other cognitive processes (e.g., spatial perception) before or during action initiation. On the other hand, motor control processes represent and compare the specific spatial features of the action goal, one's state, and how those relate to one another, with the predicted outcome of the motor plan to adjust for any mismatches online (Elliott et al., 2010; Miall & Wolpert, 1996). Offline motor planning uses gross motor features by relatively slow integrative processes, whereas online motor control uses relatively quick integrative processes to reflect moment-to-moment adaptations to the action trajectory (Thomaschke et al., 2012). Using a combination of both the multiple process model of limb control (Elliott et al., 2010) and the planning and control model (Thomaschke et al., 2012) in a complementary manner, one can better understand the underlying sensorimotor planning and control processes ongoing during goal-directed action.

A two-experiment study examined autistic performance of upper-limb goal-directed manual aiming actions requiring participants to either move their index fingers to buttons illuminated by light-emitting diodes (experiment 1) or to targets of varying sizes presented via a projector onto a tabletop (experiment 2) (Glazebrook et al., 2008). Autistic individuals showed specific differences in sensorimotor planning,

whereby preparation and initiation were typically slower with reaction times being approximately 100ms greater (Glazebrook et al., 2008). It was clear throughout the experiments that when advance information was direct, the autistic participants demonstrated a similar pattern of performance to controls. However, when advanced information required inference from the movement environment, unlike their typically developing peers, autistic participants did not use anticipatory strategies to perform a more efficient or effective movement. It may be the case that the autistic sensorimotor system has trouble simultaneously processing the multiple sources of sensory information, and facilitating their integration, for efficient motor planning. Kinematic analyses suggest that autistic individuals exhibit more temporal and spatial variability over the initial phases of movement (e.g., peak acceleration) (Foster et al., 2020a; Glazebrook et al., 2009). Notably, during rapid goal-directed aiming tasks to one of two targets, this greater variability (both temporal and spatial) over the initial movement phases occurred despite the autism group exhibiting lower peak accelerations and velocities (Glazebrook et al., 2006). This increased variability may be based on a sensorimotor planning (Foster et al., 2020a; Glazebrook et al., 2006, 2009) difficulty related to the accurate specification of forces needed for movement execution during formation of motor commands (Elliott et al., 2010; Wolpert et al., 1995). In addition to the motor planning differences in single-segment upper-limb goal-directed actions, there is evidence that autistic children do not plan sequential motor tasks in the same way as typically developing children (Fabbri-Destro et al., 2009). In a simple reach-to-place protocol, typical children significantly elongate both the reach, and place, segments when task conditions require more precision (e.g., movement times of reaching and placing are both significantly longer when a target is smaller, i.e., more precision is needed to place the object into the smaller container).

Alternatively, autistic children demonstrate a different pattern whereby the initial segment (e.g., reaching) remains consistent across experimental conditions, however, the second segment (e.g., placing) is significantly elongated when task conditions require more precision (e.g., the target is smaller). This finding indicates that typical children are considering the difficulty (i.e., smaller container = more precision) of the second segment and are modulating and planning accordingly, whereas autistic children are likely to be planning each movement phase independent of one another.

1.6 Sensorimotor Integration in Gait and Obstacle Crossing

Examinations of gait and stepping behaviour can yield extremely valuable insights into fundamental sensorimotor control processes underpinning everyday actions as we traverse about our world (e.g., walking behaviour, stepping up and down raised surfaces, adapting to changes in surface levels). Investigations into the stepping behaviour of older adults have revealed that walking over changes in surface level (e.g., an uneven pavement) and steps or staircases (e.g., both single and multiple steps) are a major cause of morbidity (Startzell et al., 2000), likely due to degraded vision in older populations (Simoneau et al., 1991; Elliott et al., 2000). A simple and cheap manipulation to the stepping environment has elicited positive benefits to alleviate the risk of falls in such populations (Foster et al., 2015; Foster et al., 2016). With an optimised horizontal-vertical visual illusion superimposed onto the face (riser) of a stair, the older adults showed increased toe clearances during ascent (Foster et al., 2015), facilitating safer climbing of stairs and promoting a safer living space. It is likely that the horizontal-vertical visual illusion significantly modulated sensorimotor integrative processes that facilitate the online perception of the obstacle (or step) as

being taller, eliciting an increase in foot clearance over the obstacle during traversal. Manipulations to the environment, such as the horizontal-vertical illusion superimposed onto the stair face, allow insight into how sensorimotor processes underpin obstacle crossing behaviours.

During everyday tasks, autistic individuals show clear sensorimotor differences that often depict a "clumsier" motor performance (Jansiewicz et al., 2006), and demonstrate more variable and less stable posture with increased lateral sway (Fournier et al., 2010b; Kohen-Raz et al., 1992; Molloy et al., 2003; Travers et al., 2013). A pattern of observable motor performance that could resemble that of an older adult. Autistic and typically developing children were asked to stand as quietly as possible with their arms by their sides for 30 seconds while standing on a force platform. Experimental manipulations isolated or modified visual, somatosensory, and vestibular afferent information to examine their integration into the sensorimotor system. The autistic sensorimotor system appeared to have difficulty with the integration of visual, vestibular, and somatosensory inputs used to maintain postural stability (Molloy et al., 2003), which may be a contributory factor to the emergence of inconsistent gait during locomotion (Rinehart et al., 2006). Throughout continuous gait, autistic individuals also demonstrate inconsistent walking "smoothness" and an increased variability of stride length (Hallett et al., 1993; Rinehart et al., 2006). During gait, the online integration of visual information is crucial for adaptive locomotion success, particularly during the approach phase of obstacle crossing (Patla, 1998; Patla & Greig, 2006). When visual information is restricted, gait dynamic stability is severely affected (Iosa et al., 2012). Alterations to spatio-temporal gait parameters (Hallemans et al., 2009a), lower-limb kinematics (Hallemans et al., 2009b), coordination between limbs (Hallemans & Aerts, 2009), and trunk stability (Moe-

Nilssen et al., 2006), all present significant disruptions when visual information is deprived. The observations of atypical postural stability and gait in autism (Molloy et al., 2003; Rinehart et al., 2006), although vision was available throughout, may be due to differences to the online integration of crucial visual information during motor execution (Patla, 1998; Patla & Greig, 2006).

1.7 Thesis Aims

Summary of Research and Overall Aims

The above sections of this introductory chapter have sought to provide crucial background and a coherent narrative to the current autism and motor control literature to offer context for the subsequent empirical chapters. Autism spectrum disorder is a neurodevelopmental disorder primarily characterised by differences in social interaction, communication, and restricted or repetitive interests (DSM-V; American Psychiatric Association, 2013). Although the clearly prominent sensorimotor control differences are not currently part of the autism diagnostic criteria, they do effectively distinguish autistic individuals from their typically developing peers (Fournier et al., 2010a; Kaur et al., 2018; Mostofsky & Ewen, 2011), and therefore warrant deeper investigation into the processes that underpin them. Kinematic analyses have facilitated an effective way to examine specific underlying sensorimotor processes implicated in altered autistic sensorimotor control (Elliott et al., 2010). In-depth observations of changes or deviations at important kinematic markers (such as peak acceleration, peak velocity, peak deceleration, and movement endpoint) allow inference of likely ongoing sensorimotor processes. The subsequent experimental chapters will seek to examine these underlying sensorimotor processes across different

tasks and autistic demographics to seek to contribute to the rapidly growing focus on autistic motor control.

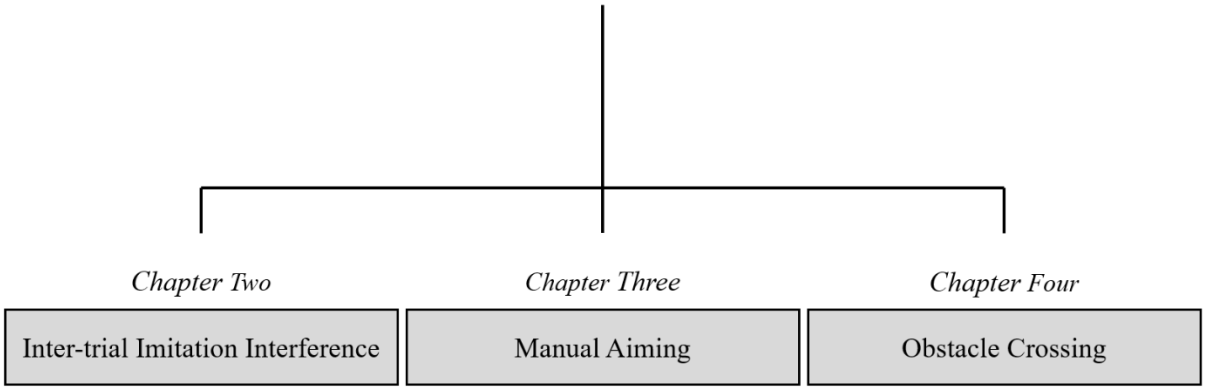

Figure 1.4: Schematic representation of the experimental chapters within this thematic thesis.

Chapter Two Aims

Initially, chapter two aims to replicate previous research demonstrating that the autistic sensorimotor system can successfully imitate both typical (i.e., representative of everyday movement) and atypical (i.e., novel) stimuli (Foster et al., 2020b). Additionally, chapter two aims to conduct a thorough kinematic examination of imitation trials to reveal the sensorimotor processes underpinning successful imitation. An examination of the contributions of offline sensorimotor processing will also be conducted to determine the importance of the inter-trial period for successful imitation.

Chapter Three Aims

Firstly, chapter three aims to examine sensorimotor planning processes in autistic and neurotypical adolescents by conducting a kinematic analysis on single-segment and two-segment manual aiming trials. This protocol will allow underlying

sensorimotor processes to be evaluated and provide evidence to understand the autistic planning and execution processes in operation during both single and two-segment manual aiming. Secondly, due to social interactive and communicative factors being fundamental to an autism diagnosis, additional experimental manipulations will facilitate an examination of underlying sensorimotor processes when instruction delivery is accompanied by a co-speech gesture.

Chapter Four Aims

This exploratory chapter aims to assess the integration efficacy of visual information into the autistic sensorimotor system by implementing a protocol requiring participants to step over a mid-walkway obstacle. Experimental manipulations will make visual alterations to the face and top edge of the obstacle. The creative methodology used in chapter four facilitates adherence to the experimental protocol in a sample of autistic participants who require substantial and/or very substantial support and are vastly underrepresented in the literature base. A descriptive account of autistic gait during obstacle crossing will accompany and complement the quantitative analyses.

Chapter Five Aims

Finally, chapter five will aim to synthesise, summarise, and appraise the key findings between experimental chapters and relative to current motor control and autism literature, to provide a coherent and easy-to-follow narrative of the underlying sensorimotor processes in operation throughout the protocols. Chapter five will engage discussion regarding themes that arise, providing both theoretical and wider implications for both the motor control and autistic communities.

2 Chapter Two: Inter-trial Imitation Interference

2.1 Introduction

Autism spectrum disorder (ASD; 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). Although not categorised as a core component of the diagnostic criteria for autism in the DSM-V, motor control and sensorimotor differences in ASD have more recently been postulated as a possible mechanism that underpins the differences seen during autistic social development (Happé, Cook & Bird, 2019).

Humans use imitation as a mechanism to learn novel actions (Hayes et al., 2016). This involves representing features associated with an observed movement performed by a model (e.g., using the hand to reach and grasp a toy) (Heyes, 2001). Imitation is not only used to learn novel actions, but it also underpins the development of social cognition (Rogers et al., 2010), interpersonal closeness and rapport (Chartrand & Bargh, 1999; Lakin & Chartrand, 2003). During imitation of biological motion (e.g., motion executed by a model), an individual observes a model displaying an outcome goal (e.g., picking up a cup) and lower-level kinematic information that depicts the movement form (e.g., limb reach and grasp kinematics). These factors (both outcome goal and movement form) are then represented within the sensorimotor system that links perception and action (Prinz, 1997). Sensorimotor planning processes control the specification of forces required to commence and maintain execution of the upcoming movement. Once execution of the movement begins, efferent and afferent sensorimotor information is integrated and compared using feedforward and feedback processes to support kinematic adjustments to the

movement profile (Wolpert et al., 1995; Wolpert et al., 1998; Wolpert et al., 2011). A sensorimotor representation is refined and updated across repeated imitation trials to become more accurate and precise over time.

Comparisons between the imitative ability of autistic and typically developing individuals has been examined previously (Hamilton, 2013; Rogers & Pennington, 1991; Vivanti & Hamilton, 2014; Vivanti & Rogers, 2014), with autistic individuals showing difficulty in representing biological motion to successfully imitate the actions of others (Hamilton, 2013; Nebel et al., 2016; Stewart et al., 2013). Behavioural data suggests this difficulty in imitation may be due to autistic individuals showing differences in sensorimotor integration (Fornier et al., 2010; Gowen & Hamilton, 2013; Hannant et al., 2016b; Hayes et al., 2016; Mostofsky et al., 2000), whereby visual and motor systems appear to be asynchronous (Nebel et al., 2016), resulting in specific differences to sensorimotor planning and specification of muscular force (Elliott et al., 2010; Foster et al., 2020a). Previous work has provided insight into the potential underlying processes and mechanisms that could influence sensorimotor integration, and in turn imitative ability, in autism (Foster et al., 2020b; Hayes et al., 2016). For example, autistic adults could successfully and accurately represent and reproduce the biological motion kinematics of a displayed model that exhibited a typical movement profile (e.g., depicting an acceleration profile akin to everyday movement) but failed to accurately reproduce the kinematics of an atypical model (e.g., depicting an acceleration profile not likely to be familiar) (Elliott et al., 2010; Hayes et al., 2016). One explanation could be that the kinematics of a typical action, as displayed by the typical model, are more likely to be represented in the sensorimotor system of internal action models which can be drawn upon to facilitate the execution of actions that are not novel. However, further examination revealed that autistic

individuals can in fact imitate both typical and atypical biological motion kinematics successfully, when experimental trials are structured in a blocked manner (Foster et al., 2020b). The blocked practice structure facilitated the imitation of biological motion by allowing participants the additional opportunity, over numerous experimental trials, to utilise sensorimotor consolidatory processes to reinforce and refine internal action models for each experimental block (Foster et al., 2020b).

Providing task goals in predictable experimental trial blocks (i.e., blocked opposed to random) has shown to facilitate the imitation of both typical (i.e., kinematics representative of typical everyday movement) and atypical (i.e., kinematics that are novel) biological motion for both controls and autistic participants (Foster et al., 2020b; Hayes et al., 2016). However, at present it is not clear whether offline or online sensorimotor consolidatory processes are responsible for the facilitation of trial-to-trial modulation and adaptation over a predictable trial block in autism (Elliott et al., 2010; Mattar & Gribble, 2005). Offline sensorimotor processes primarily occur in the period following action execution and during preparation for the upcoming action (e.g., during the inter-trial delay between trials *N* and *N+1*), on the other hand, online sensorimotor processes are primarily operational during motor performance of an action (e.g., during trial *N*) (Elliott et al., 2010; Thomaschke et al., 2012). Dual-task motor learning experiments show that the performance of an unrelated motor action during observation (e.g., rotating arms in a circular manner) reduced the beneficial effects of repeated blocked practice on subsequent motor execution (Mattar & Gribble, 2005). Additionally, repetitive Transcranial Magnetic Stimulation (rTMS) applied to the primary motor cortex (M1) during the inter-trial interval of observational practice trials, where participants performed upper-limb actions of a robotic manipulandum against varying force fields, appeared to interrupt sensorimotor integration processes

(Brown et al., 2009). rTMS during the inter-trial delay disrupted both the beneficial and detrimental effects of observation on subsequent motor performance, namely the ability to represent the sensorimotor features of a movement performed by a demonstrator (Brown et al., 2009; Hayes et al., 2010).

Previous research has demonstrated that targeting and disrupting the inter-trial delay, a likely temporal period crucial for the consolidation and refinement of internal action models, results in significant alterations to subsequent motor performance and accompanying sensorimotor control processes (Brown et al., 2009; Mattar & Gribble, 2005). It is likely that this temporal period (e.g., during the inter-trial delay between trials *N* and *N+1*) throughout an experimental block is important to facilitate the imitation of atypical biological motion kinematics for autistic participants. Therefore, the present study will interfere in this temporal period, by implementing a secondary-motor task, in an attempt to disrupt effective consolidation and refinement during imitation trial blocks. It is hypothesised that the autism group would experience a deterioration in imitation performance, and significant differences to motor planning and control processes evidenced by alterations at the kinematic level, as a result of interference in the inter-trial delay. As online processes (i.e., during motor execution) are suggested to not influence limb trajectory during the early stages of movement, it is likely that, if offline consolidatory sensorimotor processes are important for autistic imitation performance, differences would occur in early kinematic markers (i.e., acceleration and velocity) before online integrative processes can take control and make adaptations to the movement trajectory (Khan et al., 2006).

The present study first sought to replicate findings that autistic individuals can successfully imitate both typical and atypical biological motion kinematics when the imitation environment is structured to facilitate trial-by-trial processing (Foster et al.,

2020b). Secondly, a task condition was implemented to experimentally examine the contributions of the offline processing of biological motion by introducing a secondary motor task to be completed during the inter-trial delay (i.e., between trial *N* and *N+1*). If the inter-trial delay is crucial for sensorimotor processing, one would expect the secondary motor task to interfere with offline internal action model formation and consolidation, resulting in behavioural differences to execution. Finally, this study provides a comprehensive account of autistic sensorimotor control processes underpinning voluntary imitation by performing a thorough examination of goal-directed aiming actions using a well-established multiple-process model of limb control (Elliott et al., 2010).

2.2 Method

Participants

Thirty autistic participants (24 male; 6 female) and thirty typically developing control participants (24 male; 6 female) volunteered for the study. Half ($N = 15$) of the participants of each phenotype (ASD and control) were randomly assigned to two separate experimental conditions (no interference and interference). Autistic participants were recruited from an autistic society in the North West of England, and the host university. Control participants were recruited from the host university. All participants were provided with a participant information sheet and selected if they consented to be part of the study. All participants had normal or corrected-to-normal vision and were screened via self-report for the following exclusion criteria: dyspraxia, dyslexia, epilepsy and other neurological or psychiatric conditions. Participants with autism had a diagnosis of autism, Asperger's syndrome, or autism spectrum disorder

by an independent clinician. Diagnosis was confirmed by a researcher trained (with research-reliability status) in the administration of module 4 of the Autism Diagnostic Observation Schedule 2 (ADOS-2) (Lord et al., 2000). All participants with autism met the threshold for autism spectrum disorder on the ADOS-2 total classification score, and on the communication and reciprocal social interaction subscales. Groups were equated for age, and matched for full-scale IQ, and the verbal and performance subscales using the Wechsler Abbreviated Scale of Intelligence (WASI-II) (Wechsler, 1999), which was confirmed by independent samples t-tests (see Table 2.1). The experiment was designed in accordance with the 1964 declaration of Helsinki and approved by the local research ethics committee.

Table 2.1. Participant characteristics of the autism and control groups.

		Autism (*n* = 15)		Control (*n* = 15)		
		Mean (SD)	Range	Mean (SD)	Range	*t* test p value
Imitation	Chron. Age (yrs.)	22 (2)	18 – 26	20 (2)	18 – 26	0.22
	Full scale IQ	101 (11)	82 – 118	103 (9)	84 – 123	0.57
	Verbal IQ	101 (12)	87 – 127	105 (9)	89 – 126	0.37
	Performance IQ	101 (13)	79 – 119	101 (11)	82 – 117	0.99
	Gender	12M: 3F		12M: 3F		
Interference	Chron. Age (yrs.)	23 (2)	19 – 28	22 (2)	19 – 27	0.27
	Full scale IQ	107 (15)	87 – 136	107 (15)	91 – 124	0.99
	Verbal IQ	106 (15)	84 – 133	109 (8)	93 – 122	0.20
	Performance IQ	107 (16)	78 – 129	103 (13)	80 – 127	0.45
	Gender	12M: 3F		12M: 3F		

n = number of participants per experimental condition

Apparatus

Participants sat facing a 21-inch CRT monitor (Iiyama Vision Master 505) operating with a resolution of 1280 x 1024 pixels and a refresh rate of 85 Hz, located on a table at a viewing distance of approximately 555 mm. Connected to the monitor was a desktop PC (Dell Optiplex GX280), graphics tablet (Wacom Intuos Pro XL) and a hand-held stylus. Experimental stimuli were generated on the desktop PC using the COGENT toolbox (developed by John Romaya at the Laboratory of Neurobiology at

the Wellcome Department of Imaging Neuroscience) implemented in MATLAB (Mathworks Inc.).

Procedure

The imitation task required participants to observe and imitate non-human agent models (i.e., point-light dots; Johansson, 1973) displaying a single horizontal trajectory that originated from a home-position on the left-hand side of the screen and terminated at an end-position on the right-hand side of the screen. The movement amplitude of each model was 200mm and total duration was 1700ms. To examine imitation of biological motion, two models were created that displayed typical or atypical velocity profiles (Hayes et al., 2016, 2017; Andrew et al., 2016). The typical model was created by a human volunteer who practised typical goal-directed aiming actions using a hand-held stylus on a graphics tablet until a white-dot (diameter = 6.25mm), which represented the stylus cursor, moved from a home-position to an end-position in exactly 1700ms. The model displayed a typical (Flash & Hogan, 1985; Elliott et al., 2010) bell-shaped velocity profile (dashed black trace in Figure 2.1) with a peak velocity of 0.200mm/ms that occurred at 44% of the movement duration. The *atypical* model (solid black trace in Figure 2.1) was created by the same volunteer, but instead an atypical movement was practised until the 200mm amplitude was completed in 1700ms. The atypical model had a peak velocity of 0.410mm/ms that occurred at 18% of the movement duration. The method of using a human volunteer to generate both models was critical to ensure the kinematics were biological in nature and therefore it was possible to be reproduced.

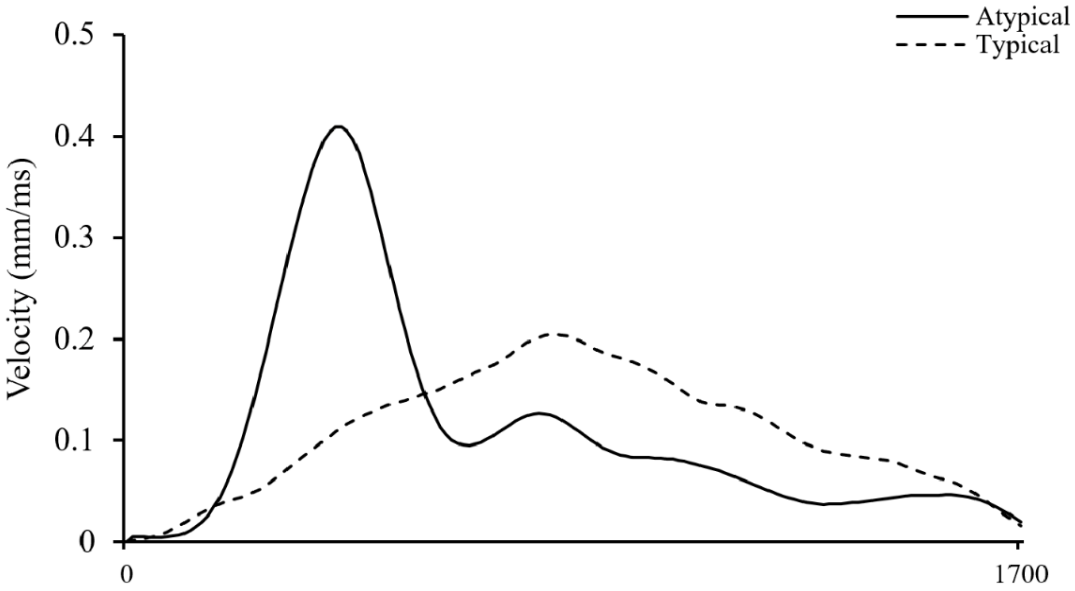

Figure 2.1: Time-series data depicting atypical (solid black trace), and typical (dashed black trace) velocity models used as experimental stimuli.

Familiarisation

Participants performed 4 familiarisation trials that replicated the task requirements of the imitation protocol. A trial commenced with participants being instructed to "watch and pay attention to the dot's trajectory, with the intention to then copy the trajectory". A non-human agent model located in the home-position then moved with a constant velocity to the end-position. The model displayed the exact movement duration and amplitude of the experimental models, but with a constant velocity in the horizontal *x* axis of 0.120mm/ms. There were no deviations in the perpendicular *y* axis. Using a constant velocity model during familiarisation trials ensured construct validity by preventing participants prematurely experiencing biological motion stimuli prior to experimental imitation trials. Participants were not informed about the duration of the movement, or the type of stimuli. After observing the model, participants imitated by moving the stylus on the tablet so that a cursor

displayed on the monitor moved from the home-position to the end-position as per the model. Participants clicked the lower-most button on a stylus to begin and end trial *N*. Following movement execution there was a 4000ms inter-trial delay period before the next model was presented for action-observation. All participants confirmed they understood the non-human agent model, the instruction on how to observe and imitate the trajectory of the model, and the sensorimotor association between the stylus on the graphics tablet and the corresponding movement of the cursor on the monitor.

No Interference Condition

The apparatus and general imitation procedure were identical to that of the familiarisation trials. The constant velocity stimuli used in the familiarisation was replaced with the typical and atypical biologically created stimuli described above. Participants performed the imitation protocol consisting of 2 blocks of 40 trials. A block contained 40 typical or 40 atypical biological motion models. The blocked order was counterbalanced across participants to control for order effects.

Interference Condition

The apparatus and general imitation procedure were identical to that of the no interference condition. Although, to induce sensorimotor interference, participants engaged in a secondary-motor task during the inter-trial delay (4000ms) between two imitation trials (e.g., during the inter-trial delay between trials *N* and *N+1*). Following motor-execution on trial *N* and before action-observation on trial *N+1,* a circular 'track' (i.e., small circle of diameter 15.78cm inside a large circle of diameter = 18.93cm) was presented on the monitor along with a white cursor (diameter = 6.25mm) that represented the position of the stylus. Participants were instructed to

move the stylus on the tablet so that the cursor moved from a start/finish position located on the right-hand side of the circle (i.e., 3 o'clock). Participants moved the cursor around the track in a clockwise direction, as many times as possible in the allocated 4000ms (identical timing to the inter-trial delay for the no interference group). This procedure was repeated across the 80 imitation trials.

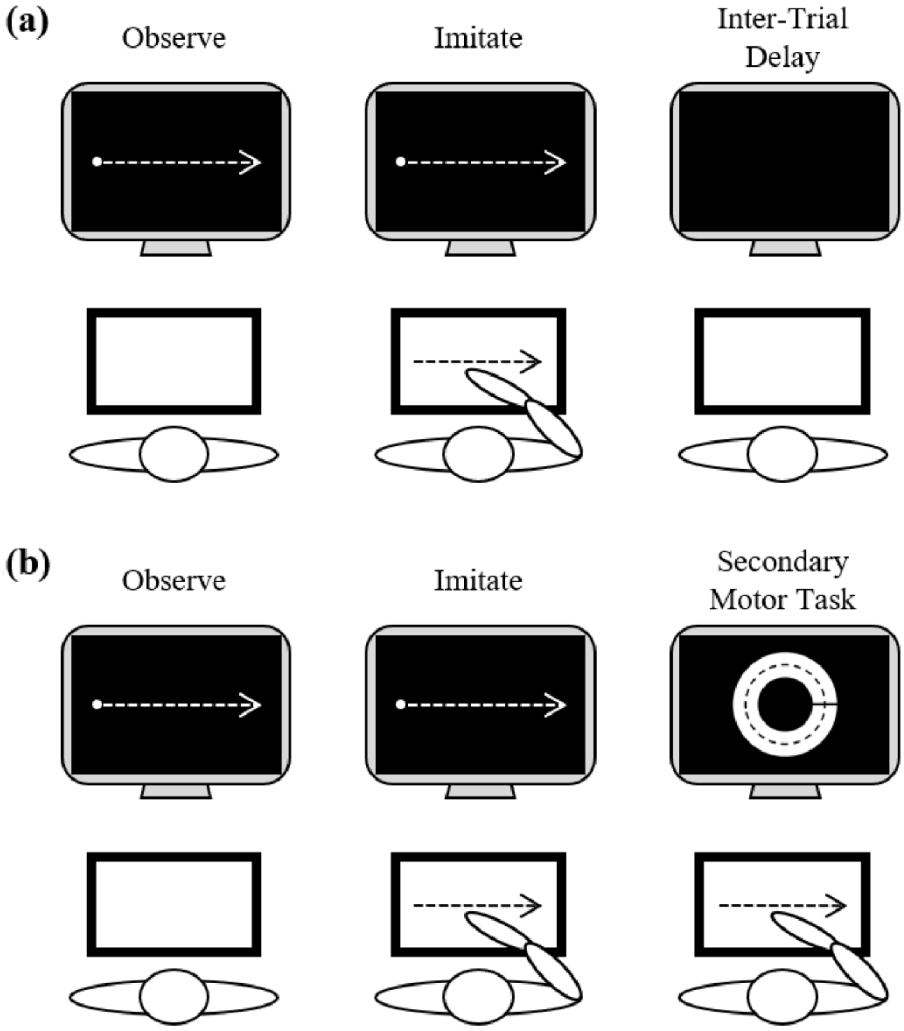

Figure 2.2: Experimental protocol for the (a) No Interference and (b) Interference task conditions.

Data Reduction and Analysis

The analysis of this study focused on the quantification of the imitation of movement kinematics in the x-axis, therefore the analysis was performed on x-axis data only. Using the x-axis position data, the start and end of each movement trial were identified. The start position was defined as the moment the centre of the cursor moved beyond the perimeter of the home-position. The end position was defined as the moment the participant pressed the lower-most button on the stylus, used to signify the end of trial *N*. For each imitation trial, the resulting position data were filtered using a low pass 4th order autoregressive filter with an 8 Hz cut-off. The filtered data were then differentiated using a 3-point central difference algorithm to obtain velocity and acceleration. A MATLAB routine extracted peak acceleration (PA), peak velocity (PV) and peak deceleration (PD). For each kinematic variable extracted, 'time to-' (ms) and 'spatial position of-' (mm) were also extracted and used to calculate 'proportional time to-' (%). Within-participant spatial variability was also calculated for each key kinematic marker.

Intra-participant means (i.e., mean data) and within-participant variability (i.e., standard deviation data) about the mean were calculated from the first twenty (i.e., early) and last twenty (i.e., late) trials performed during each forty-trial experimental block. Independent sample *t*-tests confirmed that at partitions of 10, 12, 15, 18 and 20 for early and late comparisons all dependent variables presented identical points of significance. A partition at the half-way mark (i.e., trial 20) of the forty-trial experimental block was selected to preserve the maximum number of trials included in the experimental sample to provide a more accurate and true reflection of voluntary imitation. A correlational analysis between trial *N* and trial *N+1* was conducted on a specific kinematic marker (e.g., peak acceleration) to further examine motor planning

differences across an experimental block. Pearson's r correlations were calculated for each participant, these values were translated to Z scores in order to normalise the data. Correlation analyses were performed on Z scores. All dependent variables were submitted to a 2 Group (autism; control) x 2 Task (no interference; interference) x 2 Model (atypical; typical) x 2 Phase (early-phase; late-phase) mixed design ANOVA with repeated measures on the last two factors. Significant main and interaction effects were analysed using Bonferroni-Holm post-hoc procedure to protect against Type 1 errors using a more stringent and powerful, multiple stage, statistical test (Abdi, 2010). Alpha was set at $p < 0.05$, partial eta squared (η_p^2) expressed the size of each main and interaction effect, Cohen's ds (d) expressed the size of each effect in comparisons of interest during post-hoc analysis.

2.3 Results

Timing

Movement Time

The analysis indicated main effects of model [F (1, 56) = 16.380, $p < 0.001$, $\eta_p^2 = 0.226$] and phase [F (1, 56) = 14.486, $p < 0.001$, $\eta_p^2 = 0.206$]. For the model effect, movement time was 188ms ($p < 0.05$) faster when imitating atypical (1810ms), compared to the typical (1998ms) model. For phase, movement time was 74 units ($p < 0.05$) longer when imitating in the early (1941ms), compared to the late (1867ms) phase.

There was also a group and phase interaction [F (1, 56) = 4.971, $p < 0.05$, $\eta_p^2 = 0.082$]. When imitating in the early phase, there was no significant difference between the autism (2015ms) and control (1867ms) participants ($p > 0.05$, $d = 0.40$).

There was no significant difference between the early (1867ms) and late (1836ms) phases for control participants ($p > 0.05$, $d = 0.10$), whereas autism participants executed shorter ($p < 0.05$, $d = 0.28$) movement times when imitating in the late (1898ms), compared to the early (2015ms), phase. There was no significant difference between the autism (1898ms) and control (1836ms) participants when imitating in the late phase ($p > 0.05$, $d = 0.16$). There were no other significant main or interaction effects ($ps > 0.05$).

Percentage-Time-to-Peak-Velocity

The analysis indicated main effects of task [F (1, 56) = 5.596, $p < 0.05$, $\eta_p^2 = 0.036$] and model [F (1, 56) = 96.377, $p < 0.001$, $\eta_p^2 = 0.315$]. For the task effect, percentage-time-to-peak-velocity occurred 4 units ($p < 0.05$) earlier when imitating in a blocked condition with no interference (38%) compared to a blocked condition with interference (42%). For model, percentage-time-to-peak-velocity occurred 11 units ($p < 0.05$) earlier when imitating the atypical (34%), compared to the typical (45%) model.

There was also a group and model interaction [F (1, 56) = 6.761, $p < 0.05$, $\eta_p^2 = 0.022$]. There was no significant difference between the autism (45%) and control (46%) participants when imitating the typical model ($p > 0.05$, $d = 0.12$). When imitating the atypical model, the autism (36%) participants showed a greater ($p < 0.05$, $d = 0.52$) percentage-time-to-peak-velocity than the control (31%) participants. Moreover, both the autism and control participants executed earlier ($ps < 0.05$, autism $d = 1.14$; control $d = 1.67$) percentage-time-to-peak-velocities when imitating the atypical (autism = 36%; control = 31%), compared to the typical (autism = 45%;

control = 46%), model (see Figure 2.3). There were no other significant main or interaction effects (*ps* > 0.05).

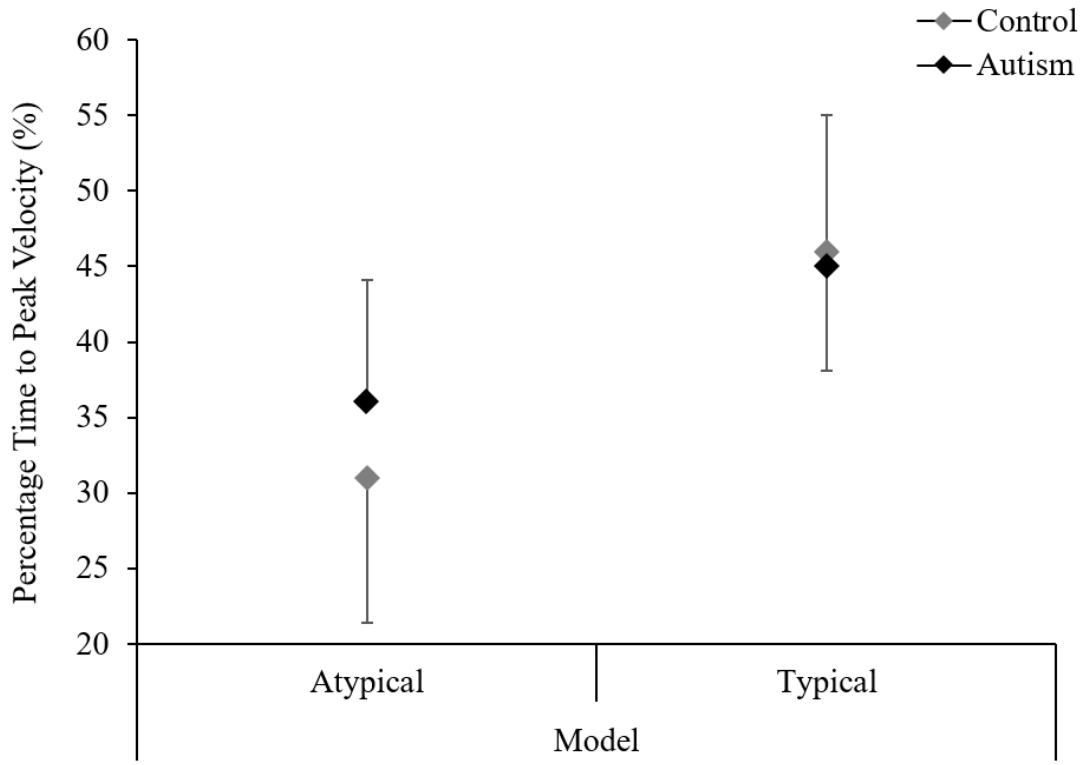

Figure 2.3: Percentage Time to Peak Velocity (%) as a function of Group and Model, error bars represent standard deviation about the mean.

Percentage-Time-to-Peak-Deceleration

The analysis indicated main effects of task [F (1, 56) = 5.367, $p < 0.05$, η_p^2 = 0.029] and model [F (1, 56) = 132.254, $p < 0.001$, η_p^2 = 0.411]. For the task main effect, percentage-time-to-peak-deceleration occurred 7 units earlier ($p < 0.05$) when imitating in a blocked condition with no interference (64%) compared to with interference (71%) in the inter-trial delay. For the model main effect, percentage-time-

to-peak-deceleration occurred 25 units earlier ($p < 0.05$) when imitating the atypical (55%), compared to the typical (80%) model.

There was also a group and model interaction [F (1, 56) = 7.928, $p < 0.05$, η_p^2 = 0.025]. There was no significant difference between the autism (79%) and control (80%) participants when imitating the typical model ($p > 0.05$, $d = 0.10$). When imitating the atypical model, the autism (60%) participants showed a greater ($p < 0.05$, $d = 0.62$) *percentage-time-to-peak-deceleration* than the control (49%) participants. Moreover, both the autism and control participants executed earlier (*ps* < 0.05, autism $d = 1.34$; control $d = 2.10$) percentage-time-to-peak-velocities when imitating the *atypical* (autism = 60 %; control = 49 %), compared to the typical (autism = 79%; control = 80%), model. There were no other significant main or interaction effects (*ps* > 0.05).

Magnitude

Peak Acceleration

The analysis indicated a main effect of group [F (1, 56) = 5.897, $p < 0.05$, η_p^2 = 0.095], task [F (1, 56) = 4.308, $p < 0.05$, $\eta_p^2 = 0.071$], model [F (1, 56) = 73.315, $p < 0.001$, $\eta_p^2 = 0.560$] and phase [F (1, 56) = 8.425, $p < 0.05$, $\eta_p^2 = 0.131$]. For group, peak acceleration was 432 units higher ($p < 0.05$) for control (2136mm/s^2) than autism (1704mm/s^2) participants. For task, peak acceleration was 370 units higher ($p < 0.05$) when imitating in a blocked condition with no interference (2105mm/s) compared to with interference (1735mm/s^2) in the inter-trial delay. For model, peak acceleration was 1236 units higher ($p < 0.05$) when imitating the atypical (2538mm/s^2), compared to the typical (1302mm/s^2), model. For phase, peak acceleration was 120 units higher

($p < 0.05$) when imitating during the late phase (1980mm/s^2), compared to the early (1860mm/s^2), phase.

There was also a group and model interaction [F (1, 56) = 9.097, $p < 0.05$, η_p^2 = 0.140]. There was no significant difference between the autism (1307mm/s^2) and control (1298mm/s^2) participants when imitating the typical model ($p > 0.05$, d = 0.02). When imitating the atypical model, the autism (2102mm/s^2) participants showed lower ($p < 0.05$, d = 0.73) peak acceleration than the control (2975mm/s^2) participants. Moreover, both the autism and control participants executed higher ($ps <$ 0.05, autism d = 1.08; control d = 1.53) peak accelerations when imitating the atypical (autism = 2102mm/s^2; control = 2975mm/s^2), compared to the typical (autism = 1307mm/s^2; control = 1298mm/s^2), model (see Figure 2.4).

There was also a group and phase interaction [F (1, 56) = 4.732, $p < 0.05$, η_p^2 = 0.078]. When imitating in the early phase, the autism (1599mm/s^2) participants showed lower ($p < 0.05$, d = 0.48) peak acceleration than the control (2121mm/s^2) participants. There was no significant difference between the early (2121mm/s^2) and late (2152mm/s^2) phases for control participants ($p > 0.05$, d = 0.02), whereas autism participants executed higher ($p < 0.05$, d = 0.25) peak accelerations when imitating in the late (1810mm/s^2), compared to the early (1599mm/s^2), phase. There was no significant difference between the autism (1810mm/s^2) and control (2152mm/s^2) participants when imitating in the late phase ($p > 0.05$, d = 0.29). There were no other significant main or interaction effects ($ps > 0.05$).

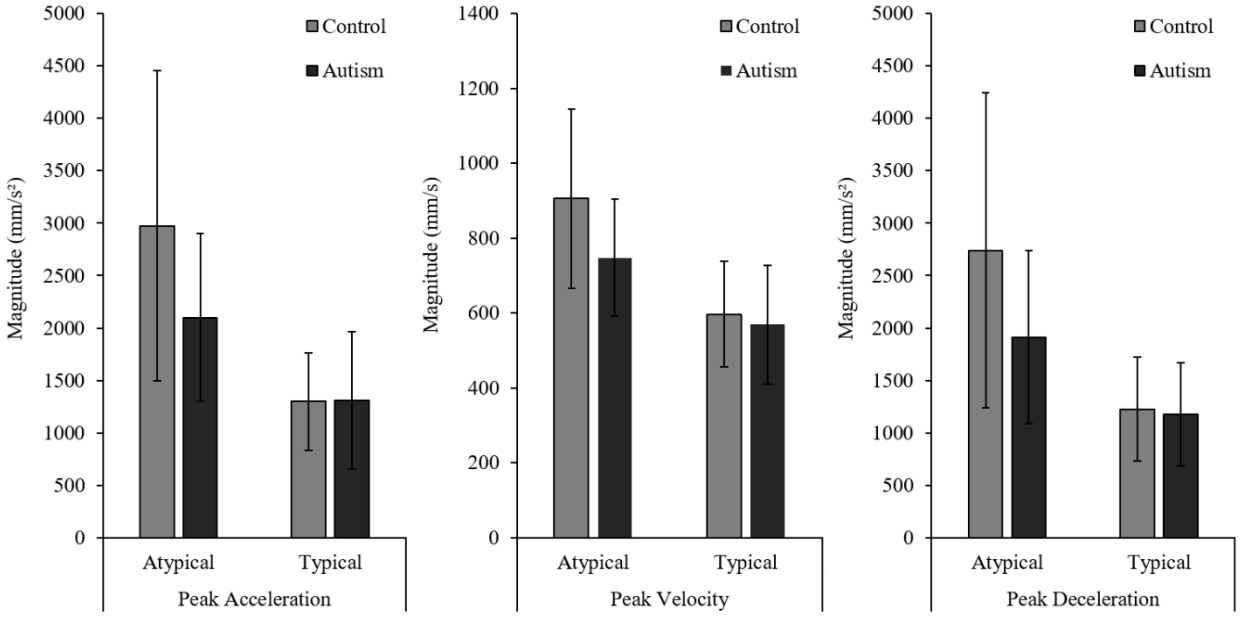

Figure 2.4: Magnitude of key kinematic markers (Peak Acceleration, Peak Velocity and Peak Deceleration) as a function of Group and Model, error bars represent standard deviation about the mean.

Peak Velocity

The analysis indicated a main effect of group [F (1, 56) = 6.835, $p < 0.05$, $\eta_p^2 = 0.109$], model [F (1, 56) = 83.142, $p < 0.001$, $\eta_p^2 = 0.598$] and phase [F (1, 56) = 12.175, $p < 0.05$, $\eta_p^2 = 0.179$]. For group, peak velocity was 92 units higher ($p < 0.05$) for control (751mm/s) than autism (659mm/s) participants. For model, peak velocity was 243 units higher ($p < 0.05$) when imitating the atypical (826 mm/s), compared to the typical (583mm/s), model. For phase, peak velocity was 31 units higher ($p < 0.05$) when imitating during the late phase (720mm/s), compared to the early (689mm/s), phase.

There was also a group and model interaction [F (1, 56) = 5.929, $p < 0.05$, $\eta_p^2 = 0.096$]. There was no significant difference between the autism (570mm/s) and

control (597mm/s) participants when imitating the typical model ($p > 0.05$, $d = 0.18$). When imitating the atypical model, the autism (748mm/s) participants showed lower ($p < 0.05$, $d = 0.77$) peak velocity than the control (905mm/s) participants. Moreover, both the autism and control participants executed higher (*ps* < 0.05, autism $d = 1.14$; control $d = 1.57$) peak velocities when imitating the *atypical* (autism = 748mm/s; control = 905mm/s), compared to the typical (autism = 570mm/s; control = 597mm/s), model (see Figure 2.4). There were no other significant main or interaction effects (*ps* > 0.05).

Peak Deceleration

The analysis indicated a main effect of group [F (1, 56) = 6.393, $p < 0.05$, $\eta_p^2 = 0.102$], model [F (1, 56) = 52.056, $p < 0.001$, $\eta_p^2 = 0.482$] and phase [F (1, 56) = 4.527, $p < 0.05$, $\eta_p^2 = 0.075$]. For group, peak deceleration was 438 units higher ($p < 0.05$) for control (1983mm/s^2) than autism (1545mm/s^2) participants. For model, peak deceleration was 1125 units higher ($p < 0.05$) when imitating the atypical (2327mm/s^2), compared to the typical (1202mm/s^2), model. For phase, peak deceleration was 92 units higher ($p < 0.05$) when imitating during the late phase (1810mm/s^2), compared to the early (1718mm/s^2), phase.

There was also a group and model interaction [F (1, 56) = 6.218, $p < 0.05$, $\eta_p^2 = 0.100$]. There was no significant difference between the autism (1177mm/s^2) and control (1226mm/s^2) participants when imitating the typical model ($p > 0.05$, $d = 0.10$). When imitating the atypical model, the autism (1913mm/s^2) participants showed lower ($p < 0.05$, $d = 0.68$) peak deceleration than the control (2740mm/s^2) participants. Moreover, both the autism and control participants executed higher (*ps* < 0.05, autism $d = 1.08$; control $d = 1.35$) peak decelerations when imitating the *atypical*

(autism = 1913mm/s^2; control = 2740mm/s^2), compared to the typical (autism = 1177mm/s^2; control = 1226mm/s^2), model (see Figure 2.4). There were no other significant main or interaction effects (*ps* > 0.05).

Spatial Variability

Variability of the Spatial Position of Peak Acceleration

The analysis indicated a main effect of group [F (1, 56) = 5.332, $p < 0.05$, $\eta_p^2 = 0.087$], task [F (1, 56) = 4.695, $p < 0.05$, $\eta_p^2 = 0.077$] and model [F (1, 56) = 4.527, $p < 0.005$, $\eta_p^2 = 0.147$]. For group, spatial variability of peak acceleration was 3.1 units higher ($p < 0.05$) for autism (12.8mm) than control (9.7mm) participants (see Figure 2.5). For task, spatial variability of peak acceleration was 2.8 units lower ($p < 0.05$) when imitating in a blocked condition with no interference (9.9mm) compared to with interference (12.7mm) in the inter-trial delay. For model, spatial variability of peak acceleration was 3.4 units lower ($p < 0.05$) when imitating the atypical (9.6mm), compared to the typical (13mm), model. There were no other significant main or interaction effects (*ps* > 0.05).

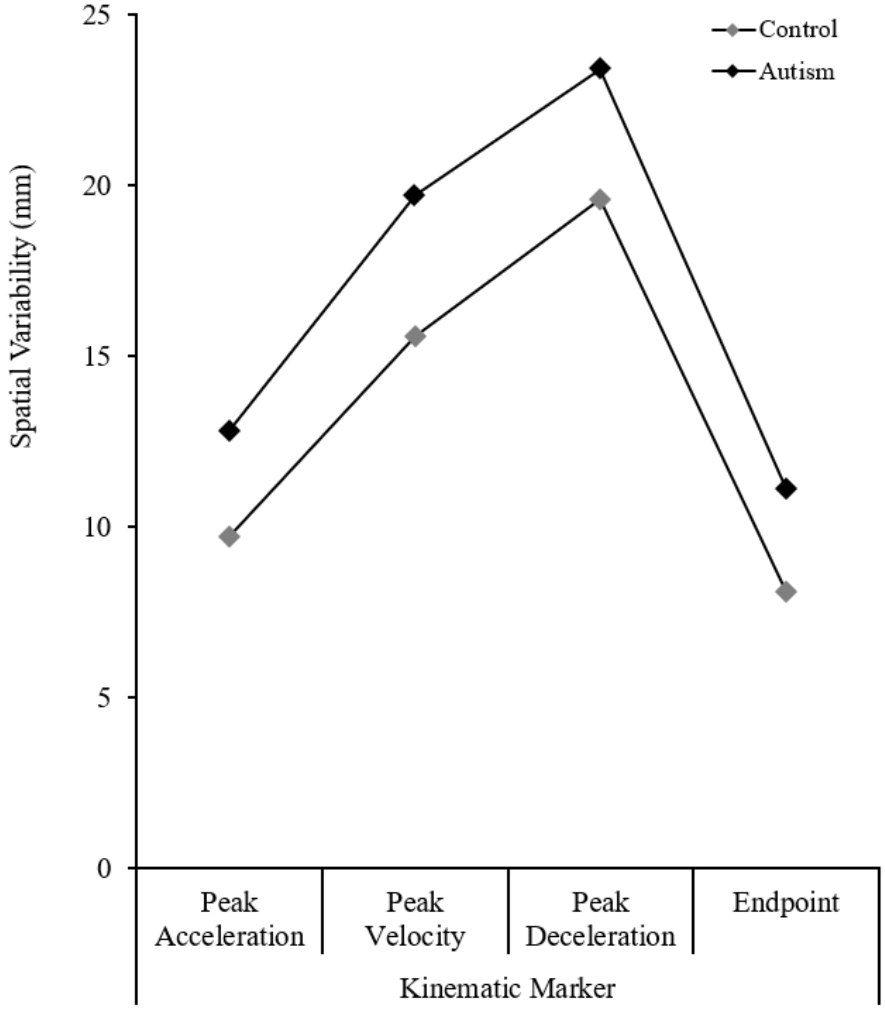

Figure 2.5: Spatial variability of key kinematic markers (Peak Acceleration, Peak Velocity, Peak Deceleration and Endpoint) as a function of Group.

Variability of the Spatial Position of Peak Velocity

The analysis indicated a main effect of group [F (1, 56) = 8.919, $p < 0.05$, η_p^2 = 0.137], model [F (1, 56) = 61.939, $p < 0.05$, η_p^2 = 0.525] and phase [F (1, 56) = 15.878, $p < 0.005$, η_p^2 = 0.221]. For group, spatial variability of peak velocity was 4.2 units higher ($p < 0.05$) for autism (19.7mm) than control (15.6mm) participants (see Figure 2.5). For model, spatial variability of peak velocity was 8 units lower ($p < 0.05$) when imitating the atypical (13.7mm), compared to the typical (21.7mm), model. For

phase, spatial variability of peak velocity was 2.3 units higher ($p < 0.05$) when imitating during the early phase (18.8mm), compared to the late (16.5mm), phase. There were no other significant main or interaction effects (*ps* > 0.05).

Variability of the Spatial Position of Peak Deceleration

The analysis indicated a main effect of group [F (1, 56) = 5.384, $p < 0.05$, η_p^2 = 0.088], task [F (1, 56) = 5.175, $p < 0.05$, η_p^2 = 0.085] and phase [F (1, 56) = 8.962, $p < 0.005$, η_p^2 = 0.138]. For group, spatial variability of peak deceleration was 3.8 units higher ($p < 0.05$) for autism (23.4mm) than control (19.6mm) participants (see Figure 2.5). For task, spatial variability of peak deceleration was 3.8 units higher ($p < 0.05$) when imitating in a blocked condition with no interference (23.4mm) compared to with interference (19.6mm) in the inter-trial delay. For phase, spatial variability of peak deceleration was 3 units higher ($p < 0.05$) when imitating during the early phase (23mm), compared to the late (20mm), phase.

There was also a model and phase interaction [F (1, 56) = 5.781, $p < 0.05$, η_p^2 = 0.094]. There was no significant difference between the early (22.7mm) and late (21.5mm) phases when imitating the typical model ($p > 0.05$, $d = 0.10$). There was no significant difference between the atypical (23.3mm) and typical (22.7mm) models when imitating in the early phase ($p > 0.05$, $d = 0.06$). When imitating the atypical model, the late (18.4mm) phase showed lower ($p < 0.05$, $d = 0.31$) spatial variability of peak deceleration than the early (23.3mm) phase. There was no significant difference between the atypical (18.4mm) and typical (21.5mm) models when imitating in the late phase ($p > 0.05$, $d = 0.31$). There were no other significant main or interaction effects (*ps* > 0.05).

Variability of the Spatial Position of Endpoint

The analysis indicated a main effect of group [F (1, 56) = 13.073, $p < 0.05$, $\eta_p^2 = 0.189$], task [F (1, 56) = 4.368, $p < 0.05$, $\eta_p^2 = 0.072$], model [F (1, 56) = 6.331, $p < 0.05$, $\eta_p^2 = 0.102$] and phase [F (1, 56) = 11.208, $p < 0.005$, $\eta_p^2 = 0.167$]. For group, spatial variability of endpoint was 3 units higher ($p < 0.05$) for autism (11.1mm) than control (8.1mm) participants (see Figure 2.5). For task, spatial variability of endpoint was 1.7 units higher ($p < 0.05$) when imitating in a blocked condition with no interference (10.4mm) compared to with interference (8.7mm) in the inter-trial delay. For model, spatial variability of endpoint was 1.7 units lower ($p < 0.05$) when imitating the atypical (10.4mm), compared to the typical (8.7mm), model. For phase, spatial variability of endpoint was 2 units higher ($p < 0.05$) when imitating during the early phase (10.6mm), compared to the late (8.6mm), phase.

There was also a model and phase interaction [F (1, 56) = 5.244, $p < 0.05$, $\eta_p^2 = 0.086$]. There was no significant difference between the early (9.2mm) and late (8.3mm) phases when imitating the typical model ($p > 0.05$, $d = 0.20$). When imitating the atypical model, the late (8.9mm) phase showed lower ($p < 0.05$, $d = 0.52$) spatial variability of endpoint than the early (12mm) phase. When imitating in the early phase, the typical (9.2mm) model showed lower ($p < 0.05$, $d = 0.49$) spatial variability of endpoint than the atypical (12mm) model. There was no significant difference between the atypical (8.9mm) and typical (8.3mm) models when imitating in the late phase ($p > 0.05$, $d = 0.12$). There were no other significant main or interaction effects ($ps > 0.05$).

There was also a task and phase interaction [F (1, 56) = 4.230, $p < 0.05$, $\eta_p^2 = 0.044$]. When imitating in the early phase, the no interference (12.1mm) condition showed higher ($p < 0.05$, $d = 0.51$) spatial variability of endpoint than the interference

(9.1mm) condition. There was no significant difference between the early (9.1mm) and late (8.3mm) phases when imitating with interference ($p > 0.05$, $d = 0.18$). When imitating with no interference, the late (8.8mm) phase showed lower ($p < 0.05$, $d = 0.53$) spatial variability of peak deceleration than the early (12.1mm) phase. There was no significant difference between the no interference (8.8mm) and interference (8.3mm) conditions when imitating in the late phase ($p > 0.05$, $d = 0.10$). There were no other significant main or interaction effects ($ps > 0.05$).

Correlation of Trial *N-N+1*

Peak Acceleration

To further evaluate sensorimotor processes relating to motor planning, peak acceleration - a key kinematic marker indicative of offline motor planning processes, was chosen for exploratory analysis. This exploratory analysis involved conducting correlation analyses on trial *N* to *N+1*. If successful motor planning occurred, one would expect positive correlations between trial *N* and *N+1* and if motor planning were interrupted or disturbed, one would expect negative correlations between trial *N* and *N+1*.

The analysis indicated a main effect of task [F (1, 56) = 15.157, $p < 0.001$, $\eta_p^2 = 0.213$]. Trial *N-N+1* peak acceleration had a stronger correlation ($p < 0.001$) when imitating in a blocked condition with no interference (Z = 0.257) compared to with interference (Z = 0.096) in the inter-trial delay. Importantly, there was also a group, task, and phase interaction [F (1, 56) = 5.229, $p < 0.05$, $\eta_p^2 = 0.085$]. The control group showed no significant differences between the trial *N-N+1* correlation of peak acceleration from early (no interference: Z = 0.355; interference: Z = 0.139) to late (no interference: Z = 0.279; interference: Z = 0.098) for either task condition ($ps >$

0.05, no interference d = 0.22; interference d = 0.16). There were also no other significant main or interaction effects for the control group (ps > 0.05). When imitating in the early phase, there was no significant differences between the trial *N-N+1* correlation of peak acceleration in the no interference (Z = 0.135), and the interference (Z = 0.167), condition for the autism group (p > 0.05). Importantly, there was a significant difference between the no interference (Z = 0.264), and interference (Z = -0.020), conditions for the autistic participants, when imitating in the late phase (p < 0.05, d = 1.01) (see Figure 2.6). From early to late practice, no interference elicited a positive correlation change (△ 96%), and interference elicited a negative correlation change (△ -112%). There were no other significant main or interaction effects for the autism group (ps > 0.05).

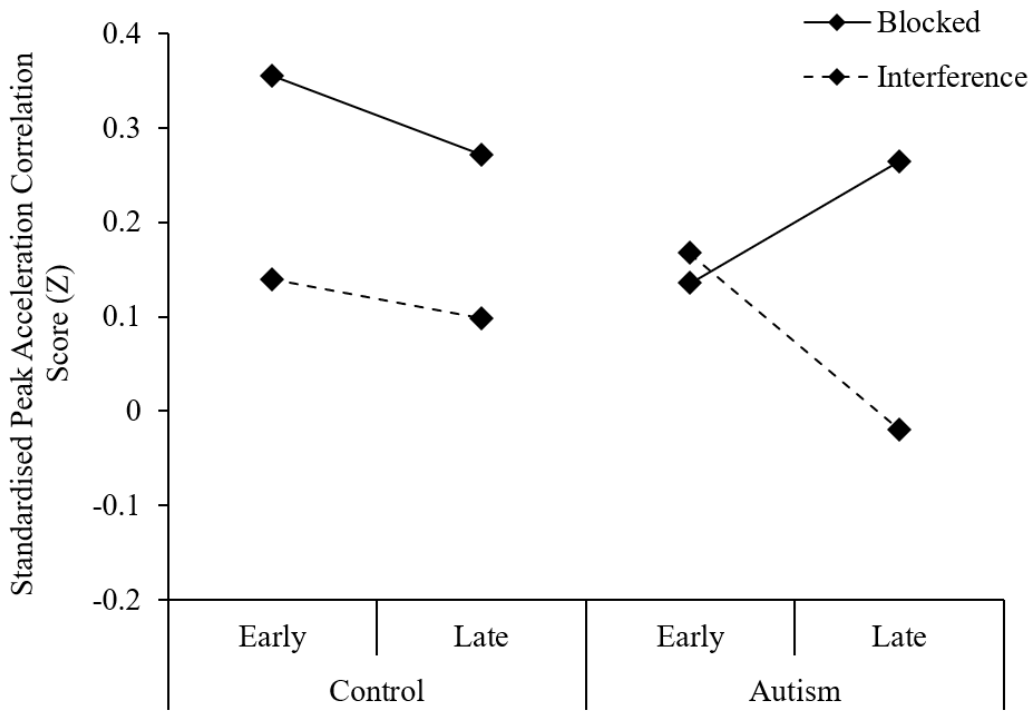

Figure 2.6: Standardised correlation scores (Z) depicting the relationship of peak acceleration on trial *N* and trial *N+1*.

2.4 Discussion

Autistic participants successfully imitated biological motion kinematics when the imitation environment was structured to facilitate trial-by-trial processing (Foster et al., 2020b). Percentage-time-to-peak-velocity (PTTPV), used as a key marker to identify the fidelity of biological motion imitation, occurred earlier when participants imitated an atypical model compared to a typical model, with controls showing a greater adaptation between atypical and typical trials (15%) than autistic participants (9%). Additionally, using a similar imitation protocol to previous work (Foster et al., 2020b; Hayes et al., 2016), offline planning, refinement and consolidation were examined by implementing a secondary motor task to disrupt the inter-trial delay following trial *N* and before trial *N+1*. This task required the drawing of concentric circles along a predetermined track during the 4000ms delay between trials. Importantly, both autistic and control groups did not differ in response to our manipulation, indicating similarities in the functioning of the sensorimotor learning system used for the processing of biological motion during voluntary imitation. However, differences between groups were found when inter-trial sensorimotor interference was implemented over an experimental trial block of 40 trials.

The timing effects of previous work were replicated whereby percentage-time-to-peak-velocity (PTTPV) occurred earlier for both autistic and control participants when imitating atypical stimuli (autism = 36%; control = 31%) compared to typical stimuli (autism = 45%; control = 46%) (Foster et al., 2020b). Previously, it was shown that autistic imitation of atypical biological kinematics did not occur (Hayes et al., 2016), potentially due to the novel action being unrepresented in the sensorimotor repertoire of internal action models to be drawn upon for motor execution. However,

the randomised structure of delivered stimuli used in Hayes et al., 2016 reduced the predictability of an upcoming model, with sensorimotor systems required to construct, deconstruct, and reconstruct sensorimotor representations (i.e., internal action models) for each individual trial (e.g., trial *N* vs trial *N+1*) (Cross et al., 2007). Implementing a structured and predictable imitation environment that facilitates the trial-by-trial processing of biological motion leads to successful sensorimotor adaptation in both autism and control groups (Foster et al., 2020b). This replicated finding, indicating that the autistic sensorimotor system can be modulated via blocked practice (Foster et al., 2020b), highlights potential applied implications for the implementation of effective sensorimotor skill interventions to improve the quality of life of autistic individuals.

Although it was shown that the autistic sensorimotor system is successfully modulating to novel stimuli during voluntary imitation of biological motion, there appears to be fundamental motor control differences occurring between autistic and control participants present across the movement profile. When imitating typical stimuli, created to be representative of a typically executed movement performed throughout everyday life (e.g., reaching for a cup), autistic participants show similar magnitudes of key kinematic markers (i.e., peak acceleration (PA), peak velocity (PV) and peak deceleration (PD)) to controls. When imitating atypical stimuli, both groups independently increase the magnitude of all key kinematic markers, which shows participants in both groups are representing the change of kinematic profile between typical and atypical stimuli during voluntary imitation. During imitation of atypical stimuli, control participants reach higher magnitudes of acceleration and velocity earlier and maintain these higher magnitudes across practice (i.e., from early- to late-phase). Although autistic participants start with lower magnitudes of acceleration and

velocity, they do increase across practice, but ultimately do not reach the higher magnitudes executed by controls. Clear group differences also occur in the spatial variability of these kinematic markers, with autistic participants remaining more variable than controls at each kinematic marker throughout the entire movement profile, from peak acceleration, through peak velocity and peak deceleration, to endpoint (Elliott et al., 2010). It is likely that the autistic sensorimotor system utilised the additional opportunity over numerous, predictable trials to refine internal action models (Wolpert et al., 1995) to imitate with increasing magnitudes of early kinematic markers (i.e., acceleration and velocity), reaching closer to the level of controls with practice (Foster et al., 2020b; Glazebrook et al., 2006; Hayes et al., 2017). Differences in early kinematic markers are indicative of specific differences in sensorimotor control processes that underpin the planning and specification of muscular force required to execute the upcoming movement (Elliott et al., 2010; Foster et al., 2020a). Potentially, the autistic sensorimotor system is compensating for the increased (spatial) variability inherent within by initially implementing lower kinematic magnitudes and modulating to increase across practice in order to facilitate effective execution using higher magnitudes (Glazebrook et al., 2006).

The contributions of the offline processing of biological motion during imitation was experimentally examined by introducing a secondary motor task to be completed during the 4000ms inter-trial delay between trial *N* and *N+1*. It is important to note that this secondary motor task requires both motor and visual processes in parallel, which are not isolated in our experiment. Should the inter-trial delay be crucial for the consolidation and refinement of important internal action models required to facilitate successful imitation, one would expect interruptions during this time to modulate sensorimotor processing and impact on performance. Importantly,

both autistic and control participants do not show differing patterns of response to one another when subject to interference (i.e., performance of a secondary motor task) during the inter-trial delay. Interference elicited lower magnitudes of early kinematic markers (i.e., acceleration and velocity), an increased spatial variability of peak acceleration, with earlier proportional times of both peak velocity and peak deceleration. Targeting a likely temporal location of the consolidatory processes involved in motor learning (e.g., interfering in the inter-trial delay) results in fundamental changes to sensorimotor behaviour, that most notably occur irrespective of group. Alterations to the early kinematic markers as a function of our interference manipulation indicate an impact on planning and feedforward control, and alterations to later kinematic markers indicate an impact on visual online control (Elliott et al., 2010). The comparable response to interference during the inter-trial delay for autistic and control participants is a positive finding that experientially identifies a lack of significant difference in the functioning of the sensorimotor system required for successful processing of biological motion used for voluntary imitation.

Contextual interference literature provides further insight into the importance of the inter-trial delay for sensorimotor processing (Brown et al., 2009; Li &Wright, 2000). More accurate motor performance when task conditions are structured to facilitate trial-by-trial processing (e.g., blocked), is disrupted by restructuring task constraints into a random order (Li &Wright, 2000). During an unpredictable sequence of trials (e.g., random) different sensorimotor representations (e.g., task *N* vs task *N+1*) are required to be constructed, deconstructed, and reconstructed across an experimental block (Cross et al., 2007), leading to increases in sensorimotor interference within the inter-trial delay (Li & Wright, 2000; Cross et al., 2007). While a random practice order may lead to benefits in long term retention, the interference

effect is suggested to have an immediate influence on sensorimotor processing and motor performance during practice (Lee & Magill, 1983). Disruption to the inter-trial consolidatory period, via Transcranial Magnetic Stimulation (TMS) to the primary motor cortex, which is known to be active during imitation processing (Nishitani et al., 2004), also significantly reduced the immediate beneficial performance effects of structured, predictable practice (e.g., blocked) (Brown et al., 2009). Modulations to early (i.e., acceleration and velocity) kinematic markers due to our interference manipulation highlight the likelihood that the inter-trial delay provides a crucial offline consolidatory period that enables efficient planning, via internal action model formation and refinement, to facilitate feedforward control processes over repeated, predictable trials across an experimental block (Elliott et al., 2010). Our consolidatory period of 4000ms is adequate to allow sufficient time for offline processing to occur, given that post-execution motor cortex activation, likely due to post-movement processing, peaks at approximately 500ms (Bender et al., 2006). Online processes (i.e., during motor execution) are suggested to not influence limb trajectory during the early stages of movement, therefore the task differences to acceleration and velocity implicate modulations to offline processing (Khan et al., 2006). The task manipulation required participants to draw concentric clockwise circles, engaging both motor and visual processes in parallel, during the 4000ms inter-trial delay following imitation on trial *N*. This explicit instruction to complete the secondary motor task between trials may have overridden the processing of the primary imitation task which resulted in disrupted sensorimotor planning.

To further examine sensorimotor planning processes in autism, an exploratory correlational analysis of peak acceleration between trial *N* and trial *N+1* was conducted. This analysis yielded a significantly weaker trial-to-trial correlation when

participants were subject to interference in the inter-trial delay over time, compared to imitating without interference. As can be seen in Figure 2.6, the control group showed no significant differences across practice for either task condition (i.e., no interference and interference). Post-hoc analyses revealed that autistic participants, however, had a significantly stronger trial-to-trial correlation when imitating without, rather than with, interference in the late phase. Graphical interpretation shows that this three-way interaction (involving Group, Task, and Phase) is driven by changes in the autism group for the no interference and interference task conditions over time, with no interference eliciting a positive correlation change (△ 96%) and interference eliciting a negative correlation change (△ -112%), from early to late practice. This finding supports previous work displaying that autistic participants, like controls, have a functioning sensorimotor system that can be modulated via blocked practice, utilising the benefit of increased opportunity for sensorimotor integration during voluntary imitation (Foster et al., 2020b). Potentially the additive impact of interference occurring during the inter-trial delay, repeatedly during an experimental block of 40 trials, resulted in the loss of strength to the trial-to-trial correlation that can be seen in the late phase for the autism group. It could be that the sensorimotor system is constrained during the inter-trial delay when under interference, continuing into the pre-planning stage of motor execution, by dividing essential resources to attempt to process multiple internal action models, reducing the effectiveness of either. In other words, during blocked practice with no interference participants can rely on a predictable and fixed trial order, allowing offline processes to facilitate the construction and continued refinement of one internal action model (e.g., the imitation task) (Elliott et al., 2010). However, when subject to interference in the inter-trial delay it could be possible that the sensorimotor system, when attempting to construct and

refine an internal action model to support imitation performance, is overridden by resources being allocated to process the secondary motor task. It may also be the case that, due to the need to perform multiple tasks on interference trials (i.e., imitation task followed by secondary motor task), there becomes a reduced reliance on prior representations resulting in a fundamental change in strategy for the autism group.

In summary, autistic participants successfully imitated biological motion kinematics when the imitation environment was structured to facilitate trial-by-trial processing (Foster et al., 2020b). During motor execution, fundamental kinematic differences were present whereby autistic participants used lower magnitudes and showed greater spatial variability than typically developing peers throughout the execution of voluntary imitation. Notably, mean results demonstrate a consistent impact on sensorimotor processing for both groups when subject to interference in the inter-trial delay. However, when subject to interference over time (from early to late practice), clear autistic differences to a key kinematic marker indicative of sensorimotor planning efficacy (i.e., peak acceleration) emerge. Increases to early spatial variability, combined with specific trial-to-trial correlation differences at peak acceleration, may implicate altered sensorimotor planning in autism. Although using a non-human agent model, findings of the present chapter could inform the structure of future imitation interventions aiming to develop the social functioning of autistic children via sensorimotor ability (Ingersoll, 2012). Findings may also inform the creation of interventions targeting sensorimotor skill development by demonstrating significant motor planning differences in ASD.

3 Chapter Three: Manual Aiming

3.1 Introduction

Autistic individuals show differences in sensorimotor control that distinguish them from non-autistic individuals (Cavallo et al., 2021; Fournier et al., 2010; Jansiewicz et al., 2006; Kaur et al., 2018; Mari et al., 2003; Marko et al., 2015; Mostofsky & Ewen, 2011). These differences are not formally classified as one of the core components of autism (as per the Diagnostic and Statistical Manual of Mental Disorders; henceforth DSM-V), but sensorimotor differences may underpin the objective, observable movement differences, including delays to the onsets of significant motor milestones (e.g., lying, righting, sitting, and crawling) during autistic development (Teitelbaum et al., 1998). Differences in sensorimotor control processes are a potential contributory mechanism underpinning how social development occurs in autism (American Psychiatric Association (APA), 2013; Happé, Cook & Bird, 2017). For example, some sensorimotor skills, such as informational gestures with the upper limbs, are a means of (e.g., wave, high-five), and/or facilitate (e.g., pointing to an object), social communication and interaction between people (Mandal, 2014). Differences in their use, quality, and quantity (Mitchell et al., 2006; Dawson et al., 1998), may impact on quality of life and functional social development in autism (Cook, 2016; Nebel et al., 2016).

Feedforward Control Differences

When performing upper-limb goal-directed actions, autistic individuals show differences in sensorimotor planning, whereby preparation and initiation is typically slower with reaction times being approximately 100ms longer (Glazebrook et al., 2008; Rinehart et al., 2001). Kinematic analysis of various upper-limb motor control

tasks has shown that autistic individuals exhibit more temporal and spatial variability over the initial phase of movement (e.g., peak acceleration) (Foster et al., 2020a). Increased variability could be based on a sensorimotor planning (Foster et al., 2020a; Glazebrook et al., 2006) difficulty related to the accurate specification of forces needed for movement execution via an internal action model (see Wolpert et al., 1995). Indeed, force production tasks have repeatedly found that autistic participants exhibit less accurate initial force contractions than controls, implicating differences to feedforward planning processes (Mosconi et al., 2015; Wang et al., 2015).

Multiple-segment Manual Aiming

In addition to the motor planning differences in single-segment upper-limb goal-directed actions, there is evidence that autistic children do not plan sequential motor tasks in the same way as neurotypical children (Fabbri-Destro et al., 2009). When required to pick up and place an object into a container, neurotypical children performed elongated movement times in the reach, and place, phases of conditions that require extra precision (i.e., small container) to complete the motor task accurately. Autistic children, however, do not modulate timing of the reach phase based on the difficulty of the subsequent phase (e.g., segment 2). Instead, autistic children only modulate timing of the place phase according to the container size (i.e., consistent with speed-accuracy relations as predicted by Fitts' law). Therefore, although there seems to be general sensorimotor feedforward planning differences in single and sequential aiming tasks in autism, it is unclear whether specific differences occur at kinematic markers pertaining to feedback control.

Although increased spatial variability at peak acceleration indicates less effective motor planning, previous work demonstrates that variability is reduced

across the movement trajectory (i.e., at other kinematic markers, e.g., peak velocity), indicating that available sensory information (e.g., vision and/or proprioception) is processed to make online corrections during movement (Foster et al., 2020a; Glazebrook et al., 2006; Khan et al, 2003). Throughout sustained force contraction tasks, autistic individuals show an increased reliance on these slower, integrative feedback mechanisms that occur as the movement progresses (Mosconi et al., 2015). Feedback-based movement corrections indicate operational sensorimotor adaptation during execution, corrections that likely inform consolidation and refinement of a developing internal action model (Haswell et al., 2009; Elliott et al., 2010, 2017; Mostofsky & Ewen, 2011).

Co-speech Gestures

It is unclear from previous work how autistic sensorimotor control processes will be impacted by the inclusion, or omission, of a direct co-speech gesture during instruction delivery of a manual aiming task. Typically, co-speech gestures, or meaningful gestures that accompany verbal speech, are described as being transitive or intransitive. Meaningful gestures that are transitive imply the use of an object (e.g., writing with a pen), whereas intransitive gestures do not (e.g., wave, high-five) (Balconi et al., 2015; Balconi et al., 2017). Although simultaneous presentation of both speech and gesture can enhance understanding, learning, transfer, and retention of information (Congdon et al., 2017), autism specific processing patterns seem to occur when co-speech gestures accompany verbal speech (Silverman et al., 2010). For example, autistic children display difficulty producing gestures either by imitation (e.g., transitive and intransitive), with tools or objects (e.g., transitive), and to produce commands (e.g., intransitive), compared to typically developing children (Dziuk et al.,

2007). Differences in the use, quality, and quantity of gestures (Mitchell et al., 2006; Dawson et al., 1998), may impact on quality of life and functional social development in autism (Cook, 2016; Nebel et al., 2016), by altering the coordination of eye contact with speech and gesture, and the interpretation of the behaviour of others (Hannant et al., 2016a). Additionally, typically developing controls more quickly identify the correct label for a depicted object when co-speech gestures accompany verbal speech, whereas autistic participants display significantly slowed identification of, and fixation to, a target when co-speech gestures were implemented (Silverman et al., 2010). These differences may be related to an autistic specificity in the use of both transitive and intransitive communicative gestures during development (Dzuik et al., 2007; Sowden et al., 2013). Therefore, the present study will implement experimental conditions whereby participants are given verbal instructions independently, or verbal instructions with a co-speech gesture conveying the task instructions (i.e., reaching to targets), to experientially examine the contributions of co-speech gestures on autistic manual aiming performance. An examination of how co-speech gestures influence underlying sensorimotor control and learning processes may help facilitate the development of classroom-based interventions that could support autistic pupil learning and educational attainment (Cook et al., 2013; Kelly et al., 2008).

In the current study, autistic sensorimotor control was examined throughout performance of the everyday phylogenetic skill of goal-directed upper-limb aiming. The primary aim was to provide a detailed kinematic analysis in order to further elucidate the autistic differences in sensorimotor control of single-segment and two-segment manual aiming (see Adam et al., 1995; Rand & Stelmach, 2010; Rand, 2018). If autistic individuals do indeed plan each segment independently (Fabbri-Destro et

al., 2009), and exhibit difficulty in specifying required muscular forces (Foster et al., 2020a), it can be expected that they would show significant differences, compared to typically developing peers, in specific kinematic markers pertaining to sensorimotor planning (e.g., spatial variability of peak acceleration and velocity, dwell time between segments). Additionally, if online feedback processes are engaged effectively, with successful adaptations to the movement trajectory being made, it can be expected that variability will reduce throughout the latter stages of movement execution (e.g., spatial variability at peak deceleration to movement endpoint) (Elliott et al., 2020; Khan et al., 2003). A secondary aim was to provide insight on the effects of a co-speech gesture during instruction delivery on underlying sensorimotor control processes. It could be expected that the presence of a co-speech gesture, and the associated social nature of such an action, would modulate the autistic sensorimotor system in a different way to typically developing controls given a fundamental part of the autistic diagnostic criteria centres around differences in social communication (American Psychiatric Association (APA), 2013; Silverman et al., 2010).

3.2 Method

Participants

Twenty-two autistic participants (17 male; 5 female) and twenty-two control participants (17 male; 5 female) volunteered for the study. Participants were recruited from two partner Special Educational Needs (SEN) schools in North Wales, a partner Special Educational Needs (SEN) school in the North West of England, and a partner secondary Academy in the North West of England. All participants (and their parents/guardians) were provided with a written and an infographic-style participant

information sheet, after which they gave their informed consent to take part. The process of gaining consent was aligned with the Mental Capacity Act (2005) and followed both an opt-out and traditional opt-in approach, dependent on organisation preference. The study protocol was designed in accordance with the 1964 Declaration of Helsinki and approved by the local research ethics committee.

Autistic participants had a diagnosis of autism, Asperger's syndrome or autism spectrum disorder given by an independent clinician. Diagnosis was confirmed via a completed teacher-report Social Responsiveness Scale-2 (SRS-2) questionnaire (Constantino & Gruber, 2012). All participants in the autism group scored in the moderate or severe range for both DSM-5 compatible scales (RRB – Restricted and Repetitive Behaviours and SCI – Social Communication and Interaction) and in the severe range for SRS-2 Total scale, indicating clinically significant differences to reciprocal social behaviour that are strongly associated with a clinical diagnosis of autism spectrum disorder. (Note: ethical approval was attained to administer the gold-standard Autism Diagnostic Observation Schedule 2 (ADOS-2) for each autistic participant to confirm clinical diagnosis for research purposes (Lord et al., 2000), however, due to the COVID-19 pandemic, access to onsite locations for face-to-face testing was restricted, and due to the sensitivity and subtlety of the ADOS-2 assessment it was not feasible to pursue online collection of this measure). Sample participant characteristics are presented in Table 3.1. All participants had normal or corrected-to-normal vision.

Table 3.1. Participant characteristics of the autism and control groups.

	Autism (*n* = 22)		Control (*n* = 22)		*t* test p value
	Mean (SD)	Range	Mean (SD)	Range	
Chron. Age (yrs.)	14.6 (2)	11 – 17	13.9 (1.5)	11 – 17	0.21
MABC-2 – Standard Total	4.4 (2.7) [a]	1 – 9	9.1 (1.9) [b]	6 – 12	1.51
SRS-2 – RRB T-score	80.55 (8.7)	66 – 90			
SRS-2 - SCI T-score	84.45 (4.5)	77 – 90			
SRS-2 – Total T-score	84.64 (4.8)	76 – 90			
Gender	17M: 5F		17M: 5F		

[a] *n* = 73%; [b] *n* = 59%

Participatory Research

The protocol implemented in this study was designed following rigorous pilot and participatory research testing in collaboration with all partner organisations (outlined above) and autistic advocates. The research team engaged in several group meetings with a selection of our previous autistic participants who were interested in becoming more involved in the research process. Having been participants previously, our advocates were familiar with our area of work and were happy to engage in a collaborative discussion to not only identify important and interesting areas of further research, but also to assist in creating and shaping future experimental protocols. Throughout these sessions, the research team were mindful of the outlined topics deemed as important to create a successful participatory research community: "Respect, Authenticity, Assumptions, Infrastructure and Empathy" (Fletcher-Watson et al., 2019). These topics remain central to our research meetings and our ongoing

relationship with our autistic advocates. Extensive discussion and pilot testing, with both our autistic advocates and Special Educational Needs Co-ordinators (SENCOs) at our partner schools, resulted in significant changes to the initially proposed experimental protocol. These co-creation meetings were fundamental and facilitated effective modifications and adjustments to be made to both the objects (i.e., use of a frog, rather than a table tennis ball) involved in the task and the type and nature of instructions provided.

Apparatus

Participants sat at a table with a fixed wooden board (70cm x 22cm x 6mm) that displayed three targets (5cm x 5cm) vertically along a midline. The centre of the closest target to the participant was 5cm from the edge of the board, and each subsequent target was located 15cm from the previous one. The three targets (depicted as lily pads) contained concentric circles (3cm x 3cm) that were yellow, blue, and red respectively (see Figure 3.1). A plastic frog (4.5cm x 3cm), which had a custom-fitted handle (0.5cm x 0.25cm) to the rear and a small reflective marker (0.5cm x 0.5cm) on the centre, was used throughout the manual aiming task. 3D data of the reflective marker was collected using two ProReflex MCU240 motion capture cameras located around the exterior of the testing room, connected via RS422 data cables to a host laptop running Qualisys Track Manager (QTM) version 2.10.

Figure 3.1: Experimental protocol used in the manual aiming task. Image shows fixed wooden board with yellow, blue, and red targets, plastic frog stationary at the home position, one motion capture camera, and infographic-style participant information sheet.

Manual Aiming Task

All participants completed single and sequential aiming actions, across experimental conditions to manipulate task instruction delivery. Upon entering the testing room, participants were asked to sit on a chair, in front of a table, where the target board was positioned. Each participant was shown the task set-up consisting of the testing laptop, motion capture cameras, target board, and object. A period of familiarisation was given to each participant allowing them to become acquainted with the object (i.e., frog) and the targets (i.e., lily pads) on the target board. All participants were informed that the required movement from target-to-target was to "make the frog jump as quickly and accurately as possible". Six participants required further explanation and clarification of this initial instruction. Once familiarised with the equipment, participants were verbally informed that they would complete a series of actions to the pre-determined targets and that they should begin by placing the frog on the yellow lily pad (i.e., the target closest to the participant). The movement conditions required the participant to move the frog to either the blue lily pad (single) or to the blue lily pad followed by the red lily pad (sequential) as quickly and accurately as possible (see Figure 3.1a and 3.1b). In the no co-speech gesture conditions, participants were given a verbal instruction to move the frog to the lily pad/s (see Figure 3.1c). In the co-speech gesture conditions, participants were given the same verbal instruction, which was accompanied with a co-speech gesture (e.g., physical pointing to target/s) (see Figure 3.1d). Each of the four experimental conditions (single no-gesture, sequential no-gesture, single gesture, and sequential gesture) were completed in blocks of 10 trials per condition, randomised and counterbalanced across participants. Importantly, all participants completed a block of 10 trials of a specific condition (e.g., single no-gesture) in one experimental testing session. In some cases,

participants completed the remaining condition blocks in a new testing session after a break.

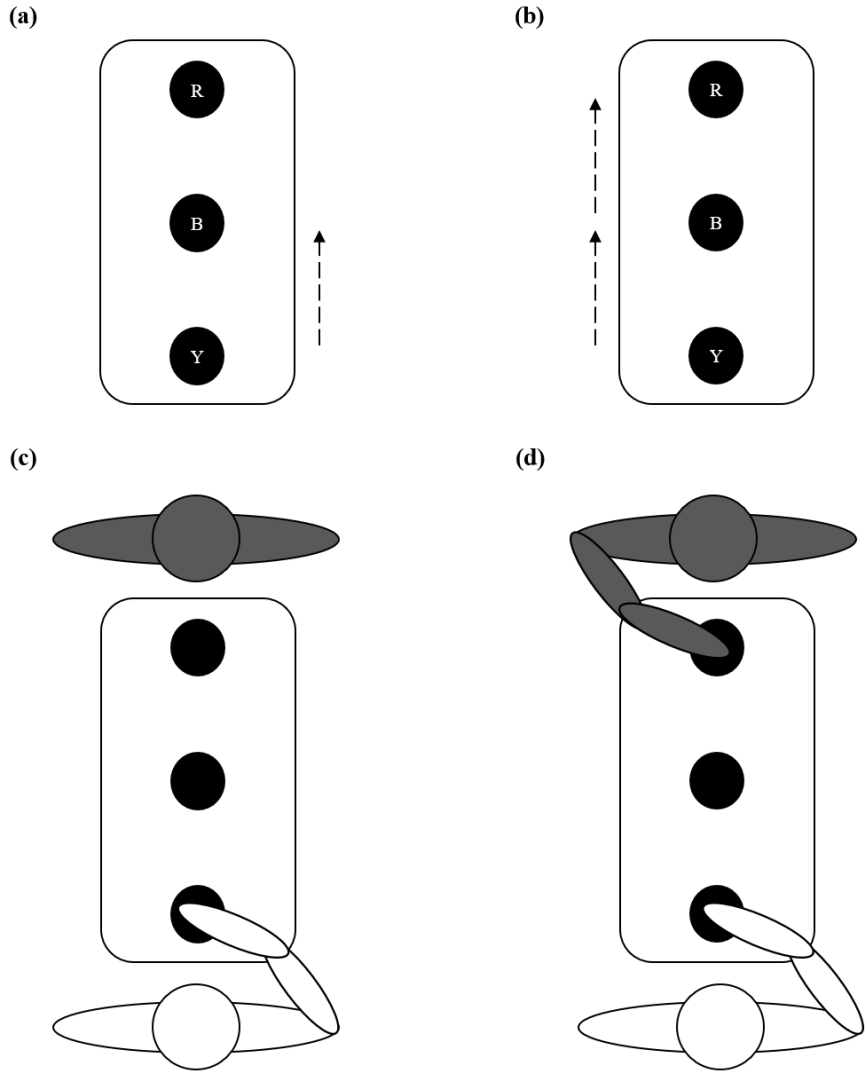

Figure 3.2: Experimental conditions manipulated in the manual aiming task: (a) single manual aiming, (b) sequential manual aiming, (c) no co-speech gesture and (d) co-speech gesture. Lettering in (a) and (b) represent colours used for targets: Y = yellow, B = blue and R = red. White model represents the volunteer, and the grey model represents the researcher.

Data Reduction and Analysis

Using the y-axis position data only (i.e., primary movement axis), movement time (from onset to offset) and dwell time (time spent following offset of segment 1 and prior to onset of segment 2 on sequential aiming trials) were identified for each experimental trial. The position data (from onset to offset) were then filtered using a low-pass 4th order autoregressive filter with a 10 Hz cut-off. The filtered data were then differentiated using a central difference algorithm to obtain velocity and acceleration data. A MATLAB custom-written routine extracted several key kinematic markers of motor control to allow a comprehensive analysis of motor behaviour for each movement segment: peak acceleration; peak velocity; peak deceleration; movement endpoint. In addition to movement time, the custom-written routine extracted and/or calculated spatial position of and peak magnitude for each of the above kinematic markers, as well as spatial position of endpoint for each segment. Constant error was calculated using the known target location and the spatial position of endpoint data to provide a measure of accuracy for each movement segment.

Intra-participant means and intra-participant standard deviation (i.e., variability) of the dependent variables were calculated from the ten experimental trials performed during each experimental block. For segment 1, these data were submitted to separate 2 Group (autism; control) x 2 Task (single; sequential) x 2 Gesture (no-gesture; gesture) mixed design ANOVA with repeated measures on the last two factors. For segment 1 and segment 2 of the sequential manual aiming conditions, these data were submitted to separate 2 Group (autism; control) x 2 Segment (segment 1; segment 2) x 2 Gesture (no-gesture; gesture) mixed design ANOVA with repeated measures on the last two factors. For dwell time and total movement time (i.e., segment 1 movement time + dwell time + segment 2 movement time) for sequential

manual aiming trials, data were submitted to separate 2 Group (autism; control) x 2 Gesture (no-gesture; gesture) mixed design ANOVA with repeated measures on the last factor. Significant interaction effects were analysed using Bonferroni-Holm post-hoc procedure to protect against Type 1 errors when using a more stringent and powerful, multiple stage, statistical test (Abdi, 2010). Alpha was set at $p < 0.05$, partial eta squared (η_p^2) expressed the size of each main and interaction effect, and Cohen's ds (*d*) expressed the size of each effect in comparisons of interest during post-hoc analysis of interaction effects. To further examine feedback-based processing, a subsidiary analysis was conducted to examine the proportional change of spatial variability from peak deceleration to endpoint. Independent samples t-tests were conducted to confirm significant magnitudes of proportional change between peak deceleration and endpoint.

3.3 Results

Segment 1 of Single and Sequential Aiming

See Tables 3.2 for timing, magnitude, magnitude variability, and spatial variability mean values for key kinematic markers across single and sequential aiming (columns 1 and 2 for below analyses)

For timing effects see Figure 3.2; for spatial variability effects see Figure 3.3

The analyses revealed a significant effect of group for movement time in segment 1 [F (1, 42) = 5.25, p < 0.05, η_p^2 = 0.111]. Across segment 1 of single and sequential manual aiming trials, autistic participants (516ms) performed segment 1 significantly faster than controls (581ms). This movement timing advantage was

performed with no significant timing variability differences between groups [F (1, 42) = 1.89, $p > 0.05$, $\eta_p^2 = 0.043$].

Further analyses revealed significant group effects for magnitude [F (1, 42) = 9.356, $p < 0.05$, $\eta_p^2 = 0.182$] and magnitude variability [F (1, 42) = 10.840, $p < 0.05$, $\eta_p^2 = 0.205$] of peak acceleration. Across segment 1 of single and sequential manual aiming trials, autistic participants (5463mm/s^2) performed segment 1 with greater magnitudes of peak acceleration than controls (3738mm/s^2). The greater magnitudes of peak acceleration were also executed with greater magnitude variability for autistic participants (1646mm/s^2) than controls (740mm/s^2). Spatial variability of peak acceleration displayed no significant differences between groups in segment 1 [F (1, 42) = 0.279, $p > 0.05$, $\eta_p^2 = 0.007$].

Although no significant differences were observed between groups for magnitude of peak velocity [F (1,42) = 0.568, p > 0.05, $\eta_p^2 = 0.013$], magnitude variability yielded a significant group effect [F (1, 42) = 17.875, $p < 0.05$, $\eta_p^2 = 0.299$]. Across segment 1 of single and sequential manual aiming trials, autistic participants (92mm/s) performed segment 1 with greater magnitude variability of peak velocity than controls (60mm/s). The greater magnitude variability of peak velocity was also executed with greater spatial variability [F (1, 42) = 37.078, $p < 0.05$, $\eta_p^2 = 0.469$] for autistic participants (14.30mm) than controls (7.28mm).

Further analyses revealed significant group effects for magnitude [F (1, 42) = 12.722, $p < 0.05$, $\eta_p^2 = 0.232$] and magnitude variability [F (1, 42) = 16.659, $p < 0.05$, $\eta_p^2 = 0.284$] of peak deceleration. Across segment 1 of single and sequential manual aiming trials, autistic participants (5522mm/s^2) performed segment 1 with greater magnitudes of peak deceleration than controls (3470mm/s^2). The greater magnitudes of deceleration were executed with greater magnitude variability for autistic

participants (1591mm/s^2) than controls (640mm/s^2). The greater magnitude variabilities of peak deceleration were also executed with greater spatial variability [F (1, 42) = 25.341, $p < 0.05$, $\eta_p^2 = 0.376$] for autistic participants (16.02mm) than controls (8.74mm). Group differences in spatial variability remained present at movement endpoint [F (1, 42) = 9.249, $p < 0.05$, $\eta_p^2 = 0.180$]. Autistic participants (7.4mm) displayed greater spatial variability at movement endpoint of segment 1 than controls (4.38mm). Importantly however, there were no significant group [F (1,42) = 1.432, $p > 0.05$, $\eta_p^2 = 0.033$], task [F (1,42) = .301, $p > 0.05$, $\eta_p^2 = 0.007$], gesture [F (1,42) = .117, $p > 0.05$, $\eta_p^2 = 0.003$], or interaction effects [F (1,42) = 0.050, $p > 0.05$, $\eta_p^2 = 0.001$] for movement endpoint error. Notably, across segment 1 of single and sequential manual aiming trials, autistic participants (17.46mm) concluded segment 1 with accuracy not significantly different to controls (21.17mm).

Segments 1 and 2 of Sequential Aiming

See Table 3.2 for timing, magnitude, magnitude variability, and spatial variability mean values for key kinematic markers across single and sequential aiming (columns 2 and 3 for below analyses)

For timing effects see Figure 3.2; for spatial variability effects see Figure 3.3

The analyses revealed a segment by group interaction for movement time [F (1, 42) = 8.547, p < 0.05, $\eta_p^2 = 0.169$]. The autism group (517ms) executed segment 1 significantly faster ($p < 0.05$, d = 0.67) than controls (581ms). There was no significant difference in movement time on segment 2 between the autism (471ms) and control (496ms) groups ($p > 0.05$), however, both groups independently performed segment 2 significantly faster than segment 1 ($ps < 0.05$, autism $d = 0.57$; control $d = 0.98$). Dwell time revealed a main effect of group [F (1, 42) = 67.548, $p < 0.05$, $\eta_p^2 = 0.617$],

whereby the autism group (128ms) spent 59ms longer ($p < 0.05$) at dwell between segment 1 and segment 2 compared to controls (69ms). Importantly, when segmental movement time and dwell time were summated, no significant group effects were present (see Figure 3.2).

Further analyses revealed significant group effects for magnitude [F (1, 42) = 9.402, $p < 0.05$, $\eta_p^2 = 0.183$] and magnitude variability [F (1, 42) = 15.826, $p < 0.05$, $\eta_p^2 = 0.274$] of peak acceleration. Across sequential manual aiming trials, autistic participants (5101mm/s^2) performed with greater magnitudes of peak acceleration than controls (3572mm/s^2). The greater magnitudes of peak acceleration were also executed with greater magnitude variability for autistic participants (1299mm/s^2) than controls (621mm/s^2). Spatial variability of peak acceleration elicited a segment by group interaction [F (1, 42) = 12.503, $p < 0.05$, $\eta_p^2 = 0.229$]. There was no significant difference in segment 1 between the autism (8.17mm) and control (8.65mm) groups. However, spatial variability of peak acceleration was greater in segment 2 for the autism (7.84mm) compared to control (3.80mm) groups. The control group showed a 4.85mm decrease ($p < 0.05$, $d = 0.67$) in spatial variability on segment 2 compared to segment 1, whereas the autism group remained relatively unchanged ($p > 0.05$, $d = 0.003$).

Although no significant differences were observed between groups for magnitude of peak velocity [F (1,42) = 0.840, $p > 0.05$, $\eta_p^2 = 0.365$], magnitude variability yielded a significant group effect [F (1, 42) = 15.755, $p < 0.05$, $\eta_p^2 = 0.273$]. Across sequential manual aiming trials, autistic participants (84mm/s) executed with greater magnitude variability of peak velocity than controls (53mm/s). The greater magnitude variability of peak velocity was also executed with greater spatial

variability [F (1, 42) = 38.326, $p < 0.05$, $\eta_p^2 = 0.477$] for autistic participants (12.86mm) than controls (6.71mm).

Further analyses revealed significant group effects for magnitude [F (1, 42) = 13.191, $p < 0.05$, $\eta_p^2 = 0.239$] and magnitude variability [F (1, 42) = 13.559, $p < 0.05$, $\eta_p^2 = 0.244$] of peak deceleration. Across sequential manual aiming trials, autistic participants (5677mm/s^2) performed segment 1 with greater magnitudes of peak deceleration than controls (3427mm/s^2). The greater magnitudes of deceleration were executed with greater magnitude variability for autistic participants (1748mm/s^2) than controls (617mm/s^2). The greater magnitude variabilities of peak deceleration were also executed with greater spatial variability [F (1, 42) = 23.748, $p < 0.05$, $\eta_p^2 = 0.361$] for autistic participants (14.32mm) than controls (8.48mm). Group differences in spatial variability remained present at movement endpoint [F (1, 42) = 14.018, $p < 0.05$, $\eta_p^2 = 0.250$]. Autistic participants (8.99mm) displayed greater spatial variability at movement endpoint than controls (5.39mm). Importantly however, there were no significant group [F (1,42) = 1.951, $p > 0.05$, $\eta_p^2 = 0.044$], gesture [F (1,42) = 1.699, $p > 0.05$, $\eta_p^2 = 0.039$], or interaction effects [F (1,42) = 0.579, $p > 0.05$, $\eta_p^2 = 0.014$] for movement endpoint error. Additionally, analyses revealed a significant task effect [F (1,42) = 104.401, $p < 0.05$, $\eta_p^2 = 0.713$], whereby segment 1 was consistently overshot by participants (19.14mm) compared to segment 2 (-2.80mm).

Table 3.2. Timing (ms), magnitude (mm/s^2, mm/s) and spatial variability (mm) of key kinematic markers across single and sequential aiming as a function of Group and Task/Segment.

		Single Segment Mean (SD)	Sequential Segment 1 Mean (SD)	Sequential Segment 2 Mean (SD)
Autism	Movement Time (ms)	514 (89)	517 (92)	471 (67)
	Mag of PA (mm/s^2)	5482 (1903)	5084 (1390)	5119 (1208)
	SV of PA (mm)	8.89	8.17	7.84
	Mag of PV (mm/s)	617 (97)	606 (86)	608 (82)
	SV of PV (mm)	15.26	13.34	12.37
	Mag of PD (mm/s^2)	5644 (1772)	5399 (1410)	5954 (2085)
	SV of PD (mm)	16.82	15.22	13.42
	SV at End (mm)	6.86	7.87	10.12
Control	Movement Time (ms)	580 (95)	581 (99)	496 (72)
	Mag of PA (mm/s^2)	3922 (759)	3553 (720)	3591 (522)
	SV of PA (mm)	8.78	8.65	3.80
	Mag of PV (mm/s)	605 (62)	577 (58)	578 (48)
	SV of PV (mm)	6.55	8.00	5.41
	Mag of PD (mm/s^2)	3593 (697)	3346 (582)	3507 (651)
	SV of PD (mm)	8.45	9.02	7.93
	SV at End (mm)	4.11	4.64	6.13

Mag = Magnitude; SV = Spatial Variability; PA = Peak Acceleration; PV = Peak Velocity; PD = Peak Deceleration; End = Endpoint

Table 3.3. Timing (ms), magnitude (mm/s^2, mm/s) and spatial variability (mm) of key kinematic markers across single and sequential aiming as a function of Group, Task/Segment and Gesture.

		No-gesture			Gesture		
		Single	Seq. 1	Seq. 2	Single	Seq. 1	Seq. 2
Autism	MT	516	511	473	513	523	470
	Mag of PA	5443	5380	5217	5521	4790	5021
	SV of PA	10.38	6.77	7.13	7.41	9.57	8.56
	Mag of PV	619	609	613	614	601	602
	SV of PV	17.68	12.49	11.83	12.85	14.19	12.91
	Mag of PD	6041	5492	5964	5247	5307	5943
	SV of PD	16.00	17.37	10.24	17.64	13.07	10.11
	SV at End	7.98	8.31	10.03	5.74	7.42	10.22
Control	MT	585	597	497	575	566	496
	Mag of PA	4143	3648	3637	3701	3459	3546
	SV of PA	10.55	9.82	3.78	7.01	7.47	3.81
	Mag of PV	623	579	580	587	576	577
	SV of PV	7.09	8.49	5.89	6.01	7.51	4.93
	Mag of PD	3744	3411	3529	3441	3281	3484
	SV of PD	8.35	8.99	9.72	8.55	9.04	8.64
	SV at End	4.28	4.78	6.14	3.94	4.50	6.13

MT = Movement Time; Mag = Magnitude; SV = Spatial Variability; PA = Peak Acceleration; PV = Peak Velocity; PD = Peak Deceleration; End = Endpoint; Single = Single segment; Seq. 1 = Sequential segment 1; Seq. 2 = Sequential segment 2.

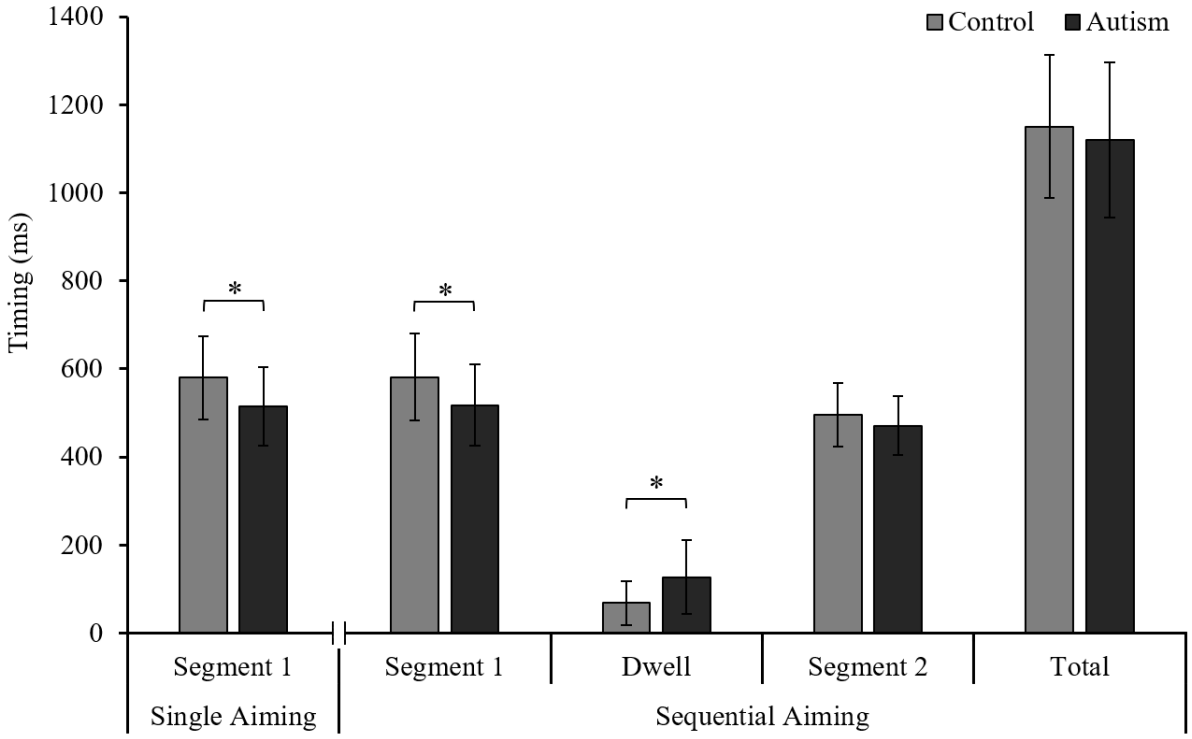

Figure 3.3: Overall timing (ms) of segment 1 of single aiming, and segment 1, dwell time, segment 2 and total timing of sequential aiming as a function of Group and Task/Segment. Total timing of sequential aiming = the sum of timing of both movement segments and dwell time. Error bars represent standard deviation of the mean.

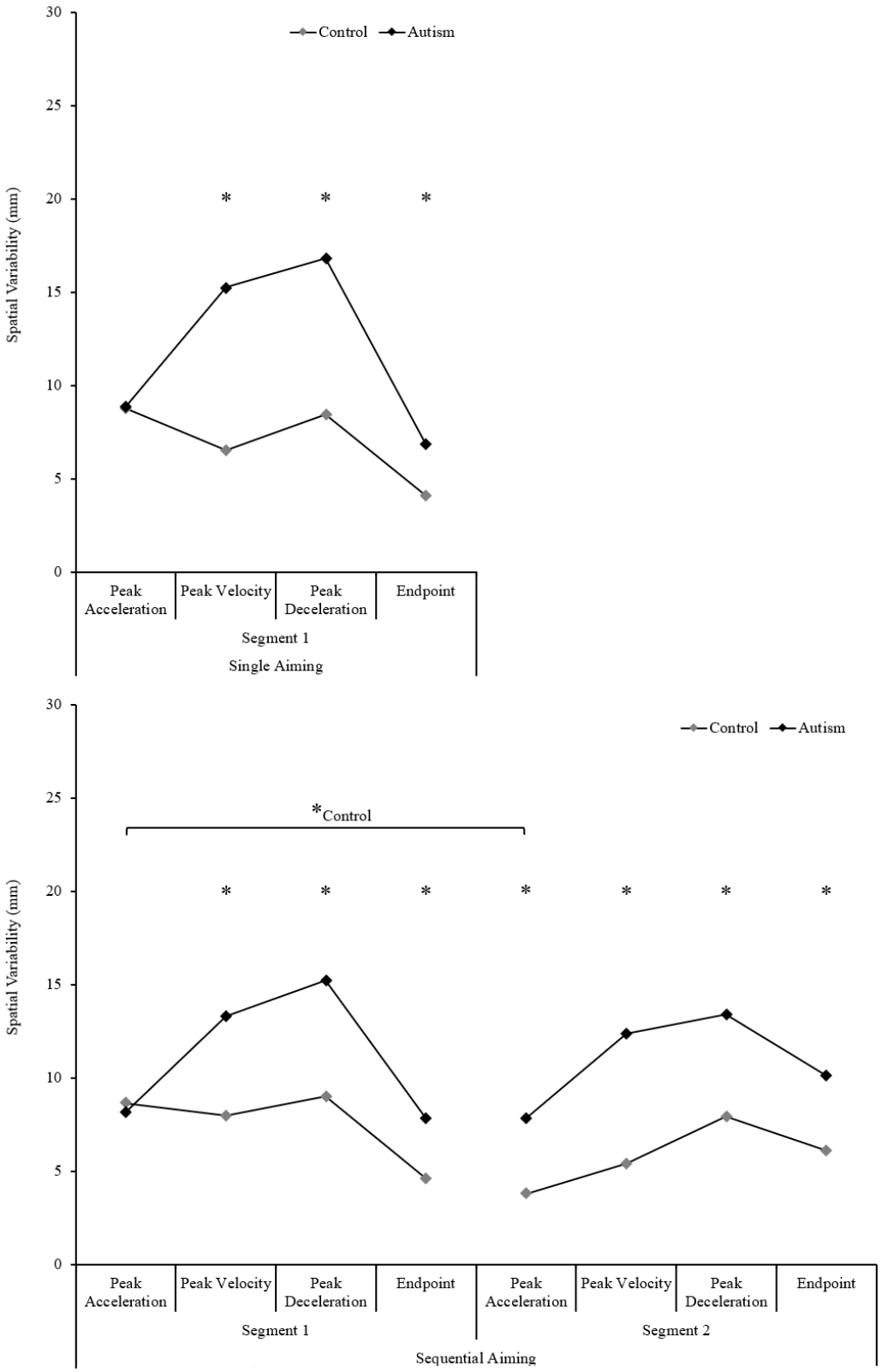

Figure 3.4: Spatial variability (mm) at each kinematic marker of segment 1 of single aiming (above), and segment 1 and segment 2 of sequential aiming (below) as a function of Group and Task/Segment.

Table 3.4. Statistical reporting of higher order three-way interaction effects. For segment 1 (a), 2 Group (autism; control) x 2 Task (single; sequential) x 2 Gesture (no-gesture; gesture). For segment 1 and segment 2 of sequential (b), 2 Group (autism; control) x 2 Segment (segment 1; segment 2) x 2 Gesture (no-gesture; gesture).

	(a) Single vs Segment 1 of Sequential	(b) Segment 1 vs Segment 2 of Sequential
MT	F (1, 42) = 2.98, $p > 0.05$, $\eta_p^2 = 0.07$	F (1, 42) = 7.22, $p < 0.05$, $\eta_p^2 = 0.147$
Mag of PA	F (1, 42) = 3.72, $p > 0.05$, $\eta_p^2 = 0.08$	F (1, 42) = 0.98, $p > 0.05$, $\eta_p^2 = 0.02$
SV of PA	F (1, 42) = 2.28, $p > 0.05$, $\eta_p^2 = 0.05$	F (1, 42) = 0.07, $p > 0.05$, $\eta_p^2 = 0.002$
Mag of PV	F (1, 42) = 3.99, $p > 0.05$, $\eta_p^2 = 0.09$	F (1, 42) = 0.001, $p > 0.05$, $\eta_p^2 = 0.00$
SV of PV	F (1, 42) = 6.53, $p < 0.05$, $\eta_p^2 = 0.134$	F (1, 42) = 0.22, $p > 0.05$, $\eta_p^2 = 0.005$
Mag of PD	F (1, 42) = 0.13, $p > 0.05$, $\eta_p^2 = 0.003$	F (1, 42) = 0.97, $p > 0.05$, $\eta_p^2 = 0.02$
SV of PD	F (1, 42) = 0.77, $p > 0.05$, $\eta_p^2 = 0.02$	F (1, 42) = 0.13, $p > 0.05$, $\eta_p^2 = 0.003$
SV at End	F (1, 42) = 1.18, $p > 0.05$, $\eta_p^2 = 0.03$	F (1, 42) = 0.23, $p > 0.05$, $\eta_p^2 = 0.006$

MT = Movement Time; Mag = Magnitude; SV = Spatial Variability; PA = Peak Acceleration; PV = Peak Velocity; PD = Peak Deceleration; End = Endpoint

Proportional Spatial Variability Change from Peak Deceleration to Endpoint

Across all movement segments (single, sequential segment 1 and sequential segment 2) both control and autism groups exhibited significant spatial variability reductions from peak deceleration to movement endpoint. On single aiming trials, both the autism (-9.9mm) and control (-4.3mm) groups significantly reduced variability by approximately 50-60% of the total variability present at peak deceleration (-59% and -51% respectively) ($p < 0.05$). On sequential aiming trials, the autism group reduced variability by 48% in segment 1 (-7.4mm) and 25% in segment 2 (-3.3mm) ($ps < 0.05$), whereas the control group reduced variability by 49% in segment 1 (-4.4mm) and 23% in segment 2 (-1.8mm) ($ps < 0.05$).

Table 3.5. Mean and proportional change in spatial variability from peak deceleration to movement endpoint.

		Single Segment	Sequential Segment 1	Sequential Segment 2
Autism	Mean SV change from PD to End (mm)	-9.9mm	-7.4mm	-3.3mm
	Proportional Variability Change (%)	-59%	-48%	-25%
	t test significance (*p)*	0.0001*	0.0001*	0.0000*
Control	Mean SV change from PD to End (mm)	-4.3mm	-4.4mm	-1.8mm
	Proportional Variability Change (%)	-51%	-49%	-23%
	t test significance (*p)*	0.0001*	0.0000*	0.0000*

SV = Spatial Variability; PD = Peak Deceleration; End = Endpoint

3.4 Discussion

A single and multiple segment manual aiming protocol was selected to provide an examination of underlying feedforward and feedback sensorimotor control processes, during the performance of a movement likely executed regularly in everyday life (e.g., picking up and placing a cup of coffee onto a coaster). In addition to the quantification of individual segment timing (i.e., movement time), specific kinematic markers were examined (peak acceleration, peak velocity, peak deceleration) to elucidate how underlying sensorimotor processes were recruited, and how these processes may differ between autistic and typically developing adolescents. Deviations at specific kinematic markers indicate alterations to specific sensorimotor control processes (such as alterations at peak acceleration being indicative of sensorimotor planning differences; Elliott et al., 2010).

Timing data indicated that, compared to typically developing controls, autistic adolescents showed a motor performance advantage (i.e., significantly shorter movement times) when executing the initial movement segment in single (66ms faster) and sequential (64ms faster) aiming tasks (see Figure 3.2). Although there was a motor performance advantage across segment one for autistic adolescents, there was no significant difference between the groups when overall movement time was quantified when performing the sequential aiming task. Overall movement time was calculated by summating segment and dwell timing across all phases of the sequential task (e.g., segment 1 + dwell + segment 2). The timing data showed that although autistic adolescents terminated segment 1 before controls, they spent almost double the time stationary at the central target prior to initiating movement in segment 2 (i.e., dwell; autism = 128ms, control = 69ms), and showed no significant differences in the

movement time of segment 2. Extended dwell times likely incorporate the processing of terminal feedback of segment 1 and facilitate sensorimotor planning of segment 2 (Adam et al., 1995). Notably, the dwell time of autistic participants (128ms) was still less than a typical movement onset latency (e.g., reaction time) to the first segment of a sequential aiming task (e.g., 220-241ms, Rand et al., 1997), thus indicating that predictive sensorimotor processes were likely used to transition between the first and second segment (Rand, 2018). In addition, kinematic data suggests that additional feedforward sensorimotor processing occurred for the control group, compared to the autism group, whereby spatial variability of peak acceleration during segment 2 of the sequential aiming task was significantly lower than spatial variability of peak acceleration in the preceding segment (e.g., segment 1). This finding indicates that sensorimotor processes for the control group facilitated the planning of the subsequent movement segment. The implication is that autistic participants were using feedforward and feedback processes to plan, control and integrate the two segments of the sequential aiming task, but they did this in a different way to typically developing control participants. Feedforward sensorimotor processes occur both prior to, and during the early stages of execution, and facilitate planning of to-be-performed actions by forming internal representations and specifying required forces for the upcoming movement (Miall & Wolpert, 1996; Mosconi et al., 2015). Feedback processes, on the other hand, occur as an executed movement progresses and can involve the utilisation of visual and proprioceptive sensory information to adapt the movement trajectory (Khan et al., 2003; Elliott et al., 2010). With movement times of around 500ms (opposed to around 150ms as seen in Khan et al., 2010), ample time is available for feedback sensorimotor processes to be engaged (Khan et al., 2003), alongside feedforward planning processes, during the initial movement segment.

Autistic differences to feedforward sensorimotor planning processes were evident in the kinematic data involving magnitude, magnitude variability and spatial variability of early kinematic markers (i.e., peak acceleration and peak velocity). In both single and sequential manual aiming tasks, the autism group exhibited greater magnitudes of peak acceleration with greater intra-participant variability in the magnitude of both peak acceleration and peak velocity. Greater spatial variabilities were also present at peak acceleration (only the second segment of sequential aiming) and peak velocity (see Figure 3.3). Based on work with typically developing adults (Slifkin & Newell, 1999), it has been suggested that increased variability in early kinematic markers (i.e., peak acceleration and peak velocity) could be due to their greater magnitude (i.e., force-variability hypothesis). While this possibility cannot be entirely discounted, it is more likely that autistic participants exhibited significantly higher spatial variability in early kinematic markers compared to typically developing controls (see also Foster et al., 2020a; Glazebrook et al., 2006) because they experienced difficulty specifying the required forces for movement execution (Mosconi et al., 2015; Wang et al., 2015) while forming internal action models (Wolpert et al., 1995) during motor planning (Elliott et al., 2010).

Autistic spatial variability differences in early kinematic markers were still evident at the later kinematic marker, peak deceleration, as well as at the endpoint of segment 1 and segment 2 (Figure 3.3). This is somewhat different to previous work (Glazebrook et al., 2006), where it was shown that an autistic difference in spatial variability at peak acceleration and peak velocity (and peak deceleration in Glazebrook et al., 2009) was no longer present at movement endpoint. That said, spatial variability at movement endpoint of both the first segment and second segment, was smaller than spatial variability at peak velocity and peak deceleration (see Figure 3.3 and Table

3.3). According to the multiple process model of goal-directed aiming and reaching (Elliott et al., 2010; Elliott et al., 2017), a reduction in spatial variability from the latter stages of aiming to movement endpoint indicates the use of online feedback control in making alterations to the movement trajectory (Khan et al., 2003; see also Elliott et al., 2020). Importantly, the autistic adolescents, despite exhibiting greater spatial variability than controls throughout, significantly reduced spatial variability from peak deceleration towards movement endpoint in magnitudes of change not dissimilar to controls. This finding indicates that online feedback control processes are operational in autism, and that the autistic sensorimotor system can make successful attempts to adapt the movement trajectory, correcting for earlier spatial variabilities during motor execution, by integrating and utilising available sources of sensory information (e.g., vision and/or proprioception) (Desmurget & Grafton, 2000; Elliott & Allard, 1985; Elliott et al., 2010; Khan et al., 2003). Despite demonstrating successful attempts to correct for early variability, the autism group end all movement segments with greater spatial variability than typically developing controls. This end-point variability indicates that although online feedback control processes facilitate a reduction in spatial variability in the latter stages of movement execution, autistic differences remain.

Contrary to hypotheses, the underlying sensorimotor control processes engaged by the autistic and control participants did not appear to be significantly different in the presence or absence of a co-speech gesture during instruction delivery. Previous work suggests clear autism specific differences are present across social orienting and joint attention (Dawson et al., 2004), involving the coordination of attention to a common referent (i.e., target/s) (Mundy, 2018), following the referential gaze (Vivanti et al., 2017), and imitating the actions of another person (Lidstone et al.,

2021b), however, when appraised alongside the findings of the current study it is likely that the reported social integrative deficits in autism are not conclusively pervasive across contexts. For example, an examination of the response to joint attention and following referential gaze using a computer monitor-mounted eye tracker found autistic children displayed an atypical response to joint attention with no attentional preference to social vs non-social stimuli (Vivanti et al., 2017). It is important to note that although participants in the present study are likely to have observed the researcher-presented informational co-speech gesture (e.g., physical pointing to target/s), including both eye contact and hand actions, this was not experimentally confirmed. It may have been advantageous to implement eye tracking in some form to experimentally determine whether the co-speech gestures were indeed observed by participants, however, the view during development of the protocol was to seek to limit any significant alterations to the ecologically valid classroom-like testing environment. In the present study, the experimental manipulation to accompany verbal instruction with a co-speech gesture was more directly related to current teaching practices in Special Educational Needs (SEN) school settings whereby a teaching assistant (TA) or teacher will often sit alongside or opposite a pupil and utilise gesture to accompany verbal instruction during performance of a task or learning exercise. As such, the current protocol (and experimental manipulations made) was developed with a view to be as ecologically valid as possible to maintain the classroom-like learning environment. The current findings extend knowledge and add to the literature base regarding social modulations in autism, may prompt further examination in this area and may be useful in informing teaching practices and to facilitate the development of classroom-based interventions to support autistic pupil learning and attainment in educational environments (Cook et al., 2013; Kelly et al., 2008).

Understanding the autistic differences to underlying sensorimotor processes involved with the planning and control of actions, and how these processes may modulate across both autistic development and changes in social context, could provide valuable evidence to inform the creation of interventions aiming to provide support during autistic development and for the early recognition of autism (Cavallo et al., 2021). An extensive body of work examining the autistic differences in sensorimotor control, underpinned by a multiple-process model of goal-directed limb control (Elliott et al., 2010; Elliott et al., 2017; Elliott et al., 2020), has demonstrated a clear and unambiguous contribution of both feedforward and feedback mechanisms of sensorimotor processing via simple but effective motor control manipulations (Foster et al., 2018; Foster et al., 2020a; Foster et al., 2020b; Hayes et al., 2018). The same sensorimotor control processes underpin imitation learning (Foster et al., 2020b) and may influence significant social developmental cascades during autistic development. Therefore, using simple but effective motor control protocols to inform the development of classroom-based interventions could provide a mechanism to facilitate autistic personal and educational attainment in the future. This may then prove to be significant in preventing or keeping at bay increasingly more pronounced motor difficulties seen throughout autistic development through adolescence to adulthood (Travers et al., 2017). Developing classification measures that can facilitate the early identification and diagnosis of autism, using motor control tasks to access sensorimotor control processes, could pave the way to early recognition and therefore the earlier implementation of support to those prone to ASD (Emanuele et al., 2021). It is also important to note that alterations to sensorimotor control processes are not solely autism specific, both Williams syndrome and Down syndrome exhibit difficulties with planning and feedback control, therefore, further examination to

underlying sensorimotor processes could be of benefit to multiple clinical groups (Elliott et al., 2006; Hocking et al., 2011).

In summary, clear sensorimotor differences were found in key kinematic markers associated with the efficacy of autistic feedforward planning and execution, as well as the integration of and transition between movement segments in sequential aiming. Notably, there were consistencies between autistic and control participants in the utilisation of feedback control processes to correct for greater spatial variabilities earlier in the movement trajectory by making online adjustments. However, clear autistic sensorimotor control differences remain present. It was also found that underlying sensorimotor control processes were not influenced by the implementation of a co-speech gesture accompanying verbal speech during instruction delivery. Importantly, this study demonstrates support for the feasibility of implementing simple but effective tasks to access crucial underlying sensorimotor control processes, involving both feedforward and feedback control, which may be useful for the early recognition of autism, and could inform and assist in the development of classroom-based interventions to aid both the personal and academic development of autistic individuals in the future.

4 Chapter Four: Obstacle Crossing

4.1 Introduction

Autism spectrum disorder (ASD; henceforth autism) is a neurodevelopmental disorder characterised by persistent deficits in social interaction and communication across multiple contexts, in combination with restricted or repetitive patterns of behaviours, interests, or activities (DSM-V; American Psychiatric Association (APA), 2013). Although the DSM-V does not yet categorise motor behaviour differences as a core component of the diagnostic criteria for autism, there is clear evidence of differences during the execution of motor actions compared to typically developing peers (Bhat et al., 2011; Fournier et al., 2010a; Hallett et al., 1993), which are observable at a young age (Teitelbaum et al., 1998). Autistic individuals are reported to exhibit clumsier motor performance of everyday tasks, such as a greater difficulty with gait and balance during locomotion (e.g., walking) (Jansiewicz et al., 2006), as well as more variable and less stable posture with increased lateral sway (Fournier et al., 2010b; Kohen-Raz et al., 1992; Molloy et al., 2003; Travers et al., 2013). Autistic individuals also often demonstrate an increased variability of stride length, a reduction in the range of motion at the ankle joint and inconsistent walking 'smoothness' with additional features such as wider step width, slower walking speed, longer gait cycle, and longer step time being particularly prevalent (Hallett et al., 1993; Lum et al., 2021; Rinehart et al., 2006b).

For typically developing individuals, impaired gait dynamic stability (Iosa et al., 2012), spatio-temporal gait parameters (Hallemans et al., 2009a), lower-limb kinematics (Hallemans et al., 2009b), coordination between limbs (Hallemans & Aerts, 2009), and trunk stability (Moe-Nilssen et al., 2006), occurs following full or partial restriction to vision during locomotion tasks. Such manipulations perturb the

typical integration of vision with other information sources (e.g., vestibular, and somatosensory) that are involved in the control of everyday locomotive actions (e.g., walking, stepping up and down raised surfaces, adapting to changes in surface levels). This raises the interesting question, then, if atypical postural stability and gait in autism (Lum et al., 2021; Molloy et al., 2003; Rinehart et al., 2006b), is in part a consequence of difficulties integrating the available information into the autistic sensorimotor system (Gowen & Hamilton et al., 2013; Lidstone et al., 2021a). In point-to-point movement tasks, the presence of a visual distractor had little impact on planning and execution processes for autistic children, whereas typically developing children were more variable in the time taken to plan movements, and initiated movements more slowly in the presence of a visual distractor (Dowd et al., 2012). This could indicate that autistic children were not successfully perceiving and integrating all available environmental cues (e.g., the visual distractor), which if processed and integrated successfully, would likely modulate the upcoming movement. Autistic differences to sensorimotor integration may be due to the prioritisation of proprioceptive, over visual, information (Haswell et al., 2009). During a task requiring control of a manipulandum against differing velocity-dependent curl force fields that perturbed motion, the autism group revealed a stronger than typical reliance on proprioception than typically developing participants (Haswell et al., 2009). These findings implicate altered sensorimotor processing and integration of visual information in autism compared to typically developing peers.

The current study utilised a simple obstacle crossing protocol in which a horizontal-vertical visual illusion was superimposed onto the face (riser) of a stair (see Foster et al., 2015) to examine sensorimotor integration in a sample of autistic adults requiring substantial support. Stepping up and onto, or over, raised surfaces depends

on the successful integration of visual information to precisely control when and how high to raise the foot to avoid making contact with the surface, and to ensure safe traversal (Patla, 1998; Patla & Greig, 2006). Typically developing participants will exhibit an increased clearance during obstacle traversal because the sensorimotor system will likely misperceive the height of the step during the approach and ascent phase due to the horizontal-vertical visual illusion (Foster et al., 2015; 2016). However, it may be hypothesised that, autistic participants would have difficulty integrating the additional available (illusory) visual information and will therefore exhibit similar stepping behaviour across experimental (i.e., horizontal-vertical visual illusion) and control (i.e., normal obstacle or obstacle emphasised using a highlighted edge) conditions. Importantly, the autistic participants in the current study were classified as requiring substantial and very substantial support, and thus this study also provides a descriptive account of autistic gait and obstacle traversal in a demographic that is vastly underrepresented in the literature base (American Psychiatric Association (APA), 2013).

4.2 Method

Participants

Seventeen autistic participants (15 male; 2 female) and twelve control participants (9 male; 3 female) volunteered for the study. Participants had normal or corrected-to-normal vision and a right-hand preference. Participants were recruited from an autistic society in the North West of England and the host University. All participants were provided with a written and an infographic-style participant information sheet, after which they gave informed consent to take part. The process of

gaining consent was aligned with the Mental Capacity Act (2005) and followed a traditional opt-in approach.

Autistic participants had a diagnosis of autism, Asperger's syndrome or autism spectrum disorder by an independent clinician and completed a Social Responsiveness Scale (Constantino & Gruber, 2012) questionnaire. All participants in the autism group scored in the moderate or severe range for both DSM-5 compatible scales (RRB – Restricted and Repetitive Behaviours and SCI – Social Communication and Interaction) and in the severe range for SRS-2 Total scale, indicating clinically significant differences to reciprocal social behaviour that are strongly associated with a clinical diagnosis of autism spectrum disorder. Substantial group differences were present regarding the participant need for support (i.e., autistic participants recruited to the study required substantial or very substantial support, with 1-1 or 1-2 support required for some, whereas control participants did not). Sample volunteer characteristics are presented in Table 4.1. The experiment was designed in accordance with the 1964 Declaration of Helsinki and approved by the local research ethics committee.

Table 4.1. Participant characteristics of the autism and control groups.

	Autism (n = 17)		Control (n = 12)		t test
	Mean (SD)	Range	Mean (SD)	Range	p value
Chronological Age (yrs.)	30 (9)	23 – 52	28 (11)	21 – 52	0.61[a]
SRS-2 – RRB T-score	76.65 (5.5)	69 – 88			
SRS-2 - SCI T-score	74.65 (6.5)	62 – 84			
SRS-2 – Total T-score	75.41 (5.9)	65 – 86			
Gender	15 M: 2 F		9 M: 3 F		

[a] *t* test conducted on unequal samples assuming unequal variance

Participatory Research

The protocol implemented in this study was designed following rigorous pilot and participatory research testing in collaboration with a partner autistic society. The research team engaged in several meetings with the activity manager and a selection of support staff and activity coaches from the autistic society to identify a suitable protocol to answer the research questions. Having been involved in these participatory research meetings previously, all involved were familiar with our area of work and were happy to engage in a collaborative discussion to not only identify important and interesting areas of further research, but also to assist in creating and shaping future experimental protocols. Collaboration with our partners at the autistic society was extremely valuable and beneficial to the overall success of the research conducted.

Apparatus

A single defined walkway (approx. 8m) was outlined for participants to walk along. A rectangular block made from medium density fibre board (approximate dimensions: W2cm, L30cm, H10cm; see Figure 4.1) was placed at the mid-point of the walkway. The block was free-standing and would tip over easily if touched (note: during the experiment, the obstacle was never knocked over). Qualisys Oqus motion capture cameras were located around the exterior of the testing area to capture three-dimensional (3D) motion as participants walked along the walkway and traversed the obstacle. Three reflective markers were placed on the top of each foot in a triangular orientation. Following fixation of the reflective markers, participants were asked to remain still for a brief period while the researcher used a digitizing wand to create virtual landmarks on the anterior- and posterior-inferior tip of each foot (i.e., toe- and heel-tips respectively). Creation of virtual landmarks prevented the need for reflective markers to be placed at crucial positions of the foot which may impede or disrupt normal walking and stepping behaviour. Two reflective markers positioned at each end of the top edge of the obstacle provided 3D co-ordinates of the obstacle position.

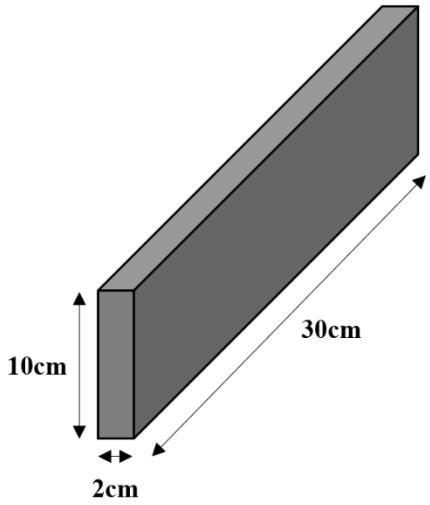

Figure 4.1: Schematic representation of the obstacle used in the obstacle crossing experimental protocol.

Obstacle Crossing Task

All participants completed obstacle crossing trials at a self-paced speed along the predetermined (8m approx.) walkway. From the set starting point, participants were asked to walk along the walkway as normal, step over the obstacle with their preferred leading-limb and resume walking to the end of the path. No instruction was given to the participants with regards to where to look during experimental trials. Experimental manipulations were made to the face and top edge of the obstacle to create three visual conditions: (a) obstacle appears as plain fibre board and is clear of any visual manipulations, (b) obstacle has a black vertical highlighted top edge, and (c) obstacle has a horizontal-vertical illusion on the face and a black strip along the top edge (see Figure 4.2). In each of the 3 conditions, participants performed 4 trials, for a total of 12 obstacle crossing trials. The presentation order of each condition was pseudo randomised for each participant. Participants were informed that they could take a break, or end the testing session, whenever they would like to.

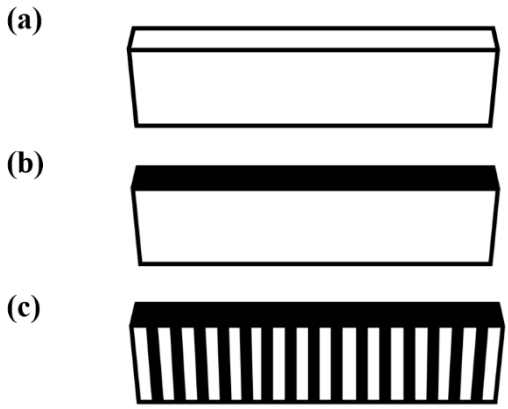

Figure 4.2: Schematic representation of visual manipulations made to the mid-walkway obstacle: (a) obstacle appears as plain fibre board, (b) obstacle contains a black vertical strip along the top edge, and (c) obstacle contains a horizontal-vertical illusion on the face and a black strip along the top edge.

Perceptual Psychophysics Task

A secondary experimental task was developed to examine whether autistic individuals succumb to the visual illusion used during the obstacle crossing task when isolated from action. In this task, participants would view schematic representations on a digital computer display of the various visual conditions used in the behavioural experiment and would be required to make determinations of height (i.e., higher, or lower) when one representation was compared to another. The view was that this perceptual task would complement the behavioural obstacle crossing data by providing more clarity and insight into perceptual processes occurring in autism, in the absence of action.

Unequal and / or Uncollected Data

Throughout the latter stages of data collection for this thesis, the global SARS-CoV-2 (COVID-19) pandemic took hold in the UK and immediately halted in-person attendance at several testing location due to government-imposed restrictions, which caused several alterations or adaptations to be made. The present chapter was the most impacted by this interruption, and as such, data collection for the initial experimental task (i.e., obstacle crossing) fell well below the expected *N* of 20 and resulted in unequal sample sizes. The planned perceptual psychophysics task could also not be conducted entirely. It is important to note that ethical approval for this task was attained prior to restrictions being imposed.

Data Reduction and Analysis

Qualisys output data were anatomically labelled using a predetermined format (as in Foster et al., 2016) and uploaded to Visual3D to perform a biomechanical analysis of obstacle crossing. Marker trajectories were smoothed with a low-pass 4th order autoregressive filter with a 6 Hz cut-off. Key dependant variables related to obstacle crossing performance were determined and extracted for each trial (lead limb vertical toe clearance, lead limb max toe elevation and lead limb vertical heel clearance) (see Figure 4.3). Toe and heel clearance were determined as the vertical distance between the toe- and heel-tips of the leading limb and the top edge of the obstacle. Max toe elevation was determined as the greatest vertical distance from ground level during the obstacle crossing swing phase. Resultant foot velocity was extracted during the leading limb swing phase over the obstacle. The leading limb swing phase was defined as occurring between the lifting of the leading limb prior to traversing the obstacle, until the final foot placement of the leading limb following traversal of the obstacle.

Intra-participant means and standard deviations were calculated from the block of four trials per visual condition. These data were firstly submitted to separate 2 Group (autism; control) x 2 Visual Condition (plain; illusion) mixed design ANOVAs with repeated measures on the last factor. Alpha was set at $p < 0.05$, partial eta squared (η_p^2) expressed the size of each main and interaction effect. A lack of homogeneity between the group sample sizes, and variance, was apparent prior to conducting the analyses, and as such, data were analysed using planned comparisons in order to preserve statistical power (Rusticus & Lovato, 2014). The two sets of orthogonal planned comparisons to examine specific hypotheses were then conducted for each dependent variable (see Figure 4.3). The first set of planned comparisons (C1)

compared no visual manipulation (plain) to the addition of a visual manipulation (highlighted edge and illusion) for control and autism groups. The second set of planned comparisons (C2) compared no visual manipulation (plain) to the addition of a horizontal-vertical illusion (illusion) to the obstacle face for control and autism groups. Additional descriptive and exploratory analyses were conducted to aid data interpretation.

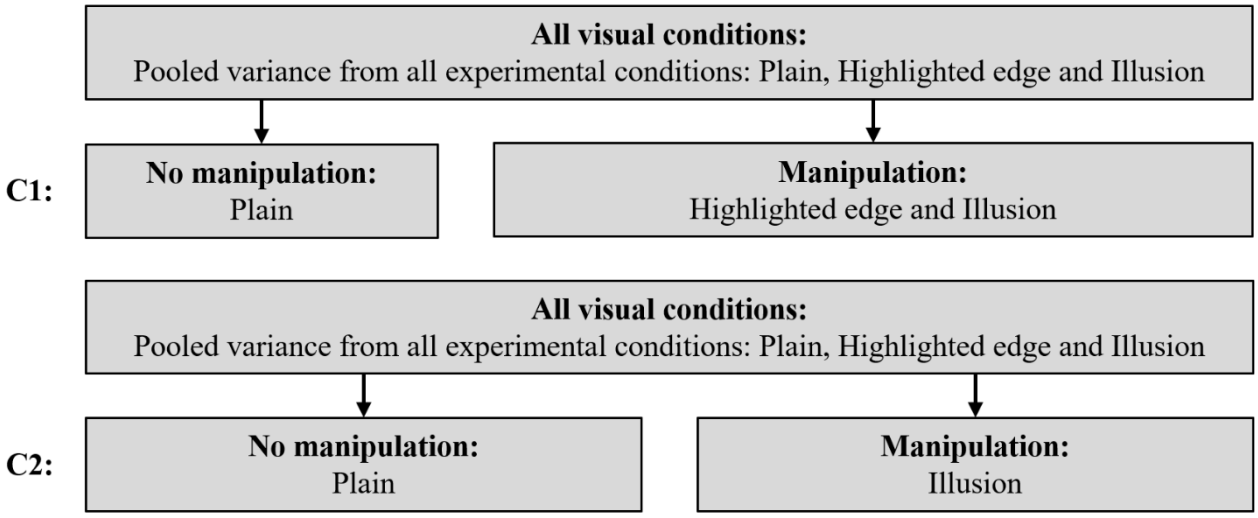

Figure 4.3: Schematic representation of orthogonal planned comparisons: (C1) comparing no visual manipulation (plain) to the addition of a visual manipulation (highlighted edge and illusion), and (C2) comparing no visual manipulation (plain) to the addition of a horizontal-vertical illusion (illusion).

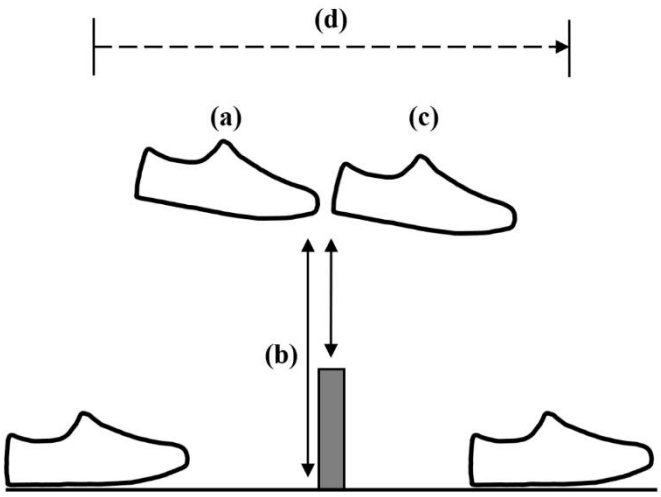

Figure 4.4: Schematic representation of key dependent variables extracted during obstacle crossing: (a) leading limb vertical toe clearance over the obstacle, (b) leading limb max toe elevation during the swing phase, (c) leading limb vertical heel clearance over the obstacle, and (d) resultant foot velocity throughout the obstacle crossing swing phase. The grey box represents the obstacle, the white shoe icons represent the leading limb throughout the swing phase (adapted from Foster et al., 2016).

4.3 Results

Time Series Analysis

An exploratory, qualitative description of exemplar toe clearance and resultant foot velocity provides insight into representative autistic and typically developing stepping and obstacle traversal. As can be seen in Figure 4.4, representative autistic participants show increased variability of toe clearance (standard deviation expressed via grey shading) throughout the swing phase compared to controls. This variability appears to peak at approximately 50-55% of the swing phase. Participant (i) demonstrates a bell-shaped variability profile that appears to consistently increase to the peak toe clearance and proceeds to decrease towards the swing phase termination.

Participant (ii) demonstrates little within-participant variability, in plain and illusion conditions, across the early swing phase, but then elicits greater variability in the later swing phase. Across autistic participants, there appears to be little difference between plain and illusion conditions. In comparison, both control participants (iii) and (iv) show a consistent pattern of increased variability towards the onset of vertical toe clearance and max toe elevation, with a reduction of variability between vertical toe clearance and vertical heel clearance, irrespective of visual condition.

As can be seen in Figure 4.5, like toe clearance, representative autistic participants (i) and (ii) show increased variability of resultant foot velocity (standard deviation expressed via grey shading) throughout the swing phase compared to controls. However, unlike toe clearance, autistic exemplar plots of velocity display inconsistent variability peaks throughout both the early and late swing phase. Conversely, control participants display a much more consistent velocity profile, with little variability in the initial stages of the swing phase and increases to variability around the velocity peak. Both exemplar control participants (iii) and (iv) also demonstrated consistent patterns of variability across visual conditions. Comparison of the mean velocity traces between autistic and control participants shows that both autistic participants exhibited multiple mean velocity peaks, seemingly one in the early and one in the late swing phase, whereas control participants exhibited a much 'smoother', typical bell-shaped velocity profile. This qualitative description of exemplar, representative participant plots is supported and expanded below via multiple discrete dependant variables that are crucial to an examination of stepping and obstacle traversal performance.

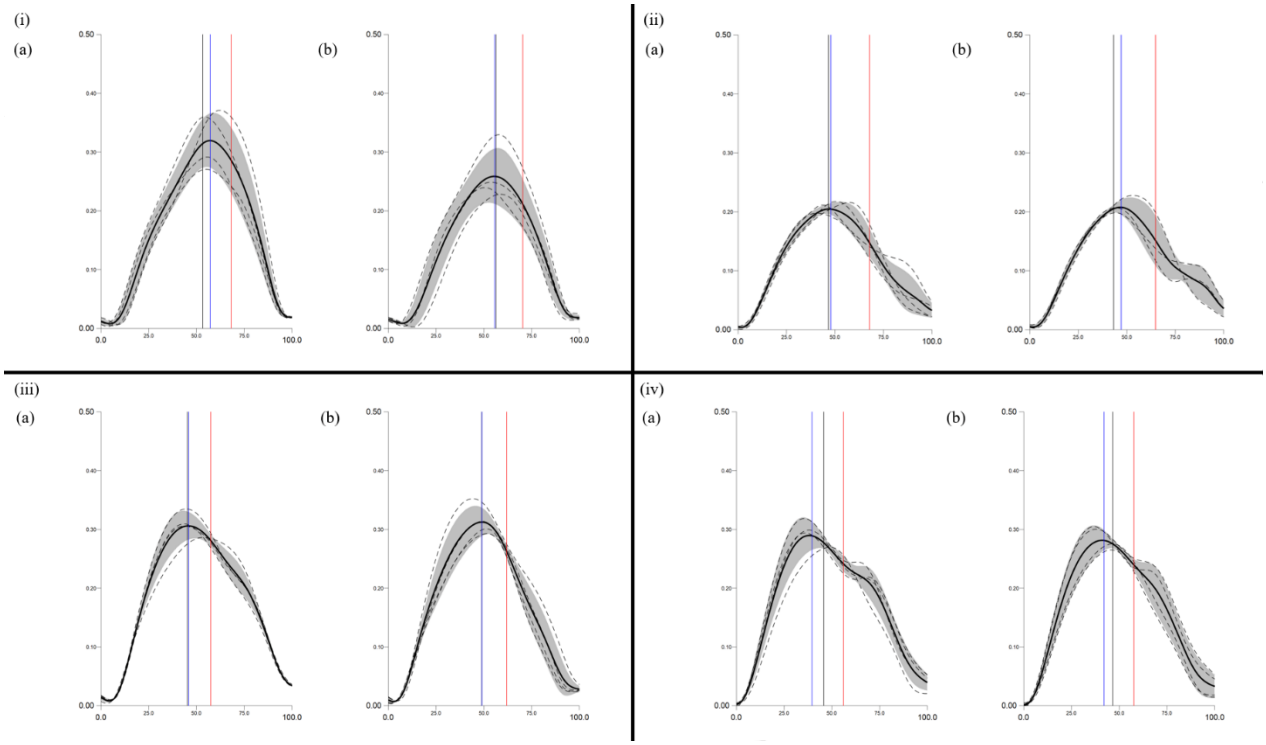

Figure 4.5: Vertical toe clearance during the obstacle crossing swing phase (%) for two autism (i) (ii) and two control (iii) (iv) group participants – each panel represents individual exemplar participant data across plain (a) and illusion (b) conditions respectively. The x-axis depicts swing phase progress (%), the y-axis depicts vertical toe clearance (m). Vertical lines intersecting the x-axis represent specific landmarks of obstacle crossing: Black = mean vertical toe clearance, red = mean vertical toe clearance, blue = mean max toe elevation.

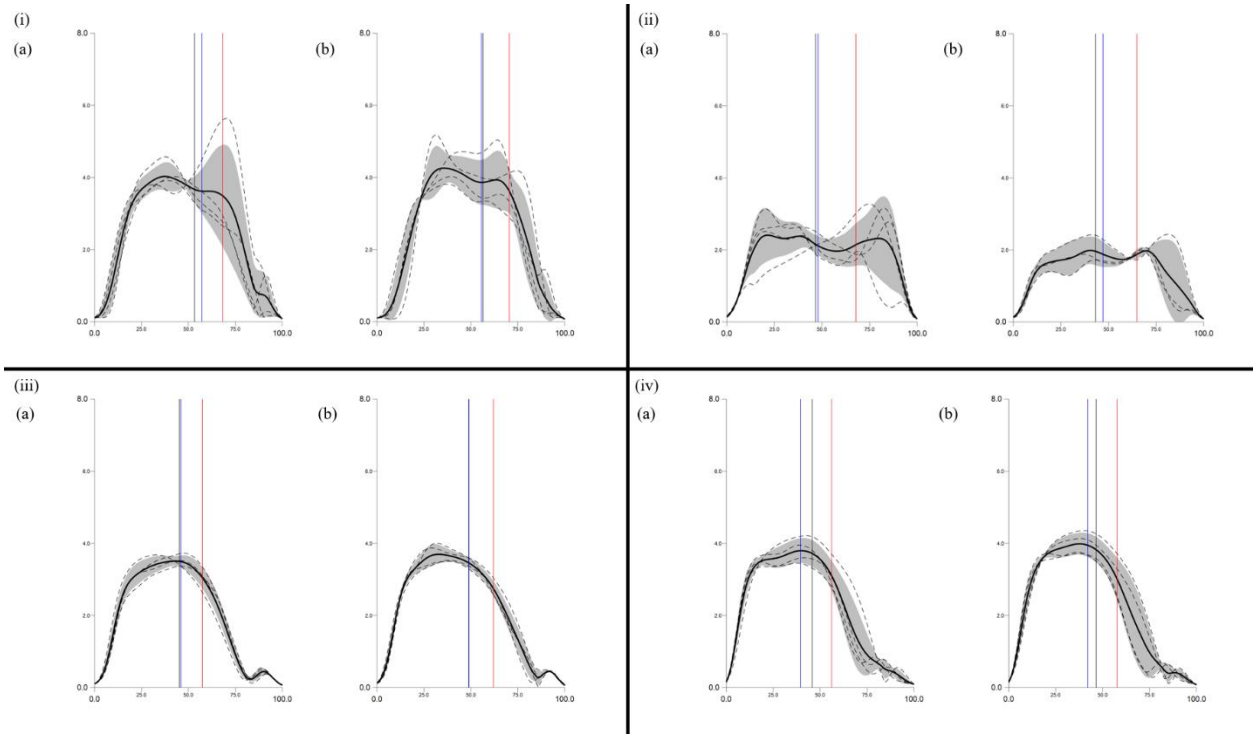

Figure 4.6: Resultant foot velocity during the obstacle crossing swing phase (%) for two autism (i) (ii) and two control (iii) (iv) group participants – each panel represents individual exemplar participant data across plain (a) and illusion (b) conditions respectively. The x-axis depicts swing phase progress (%), the y-axis depicts foot velocity (m/s). Vertical lines intersecting the x-axis represent specific landmarks of obstacle crossing: Black = mean vertical toe clearance, red = mean vertical toe clearance, blue = mean max toe elevation.

Variability Analysis

Leading Limb Vertical Toe Clearance

There was a main effect of group [F (1, 27) = 4.933, $p < 0.05$, $\eta_p^2 = 0.154$]. Variability was 1.9cm greater ($p < 0.05$) for autism (3.5cm) than control (1.6cm) participants. There were no other significant main or interactions effects.

Leading Limb Max Toe Elevation

There was a main effect of group [F (1, 27) = 6.592, $p < 0.05$, $\eta_p^2 = 0.196$]. Variability was 2.7cm greater ($p < 0.05$) for autism (3.9cm) than control (1.2cm) participants. There were no other significant main or interactions effects.

Leading Limb Vertical Heel Clearance

There was a main effect of group [F (1, 27) = 4.485, $p < 0.05$, $\eta_p^2 = 0.142$]. Variability was 1.2cm greater ($p < 0.05$) for autism (3cm) than control (1.8cm) participants. There were no other significant main or interactions effects.

Planned Comparisons

Control Group

The first set of planned comparisons (C1) revealed that there were no significant effects of a visual manipulation to the obstacle for either leading limb vertical toe clearance [t (33) = -0.558, $p > 0.05$], leading limb max toe elevation [t (33) = -0.596, $p > 0.05$], or leading limb vertical heel clearance [t (33) = -0.962, $p > 0.05$].

The second set of planned comparisons (C2) revealed that there were no significant effects following the addition of a horizontal-vertical visual illusion to the obstacle face for either leading limb vertical toe clearance [t (33) = -0.609, $p > 0.05$],

leading limb max toe elevation [t (33) = -0.681, p > 0.05], or leading limb vertical heel clearance [t (33) = -1.332, p > 0.05].

Despite significant effects not being present across planned comparisons, visual examination of within-participant difference scores between the plain and illusion conditions revealed that across all key dependent variables of obstacle traversal (leading limb vertical toe clearance, leading limb max toe elevation, and leading limb vertical heel clearance) control participants were likely influenced by the illusion (75%, 75%, and 92% respectively).

Autism Group

The first set of planned comparisons (C1) revealed that there were no significant effects of a visual manipulation to the obstacle for either leading limb vertical toe clearance [t (48) = -0.364, p > 0.05], leading limb max toe elevation [t (48) = -0.371, p > 0.05], or leading limb vertical heel clearance [t (48) = -0.192, p > 0.05].

The second set of planned comparisons (C2) revealed that there were no significant effects following the addition of a horizontal-vertical visual illusion to the obstacle face for either leading limb vertical toe clearance [t (48) = -0.397, p > 0.05], leading limb Max toe elevation [t (48) = -0.560, p > 0.05], or leading limb vertical heel clearance [t (48) = 0.088, p > 0.05].

With significant effects not being present across planned comparisons, visual examination of within-participant difference scores between the plain and illusion conditions also revealed that across all key dependent variables of obstacle traversal (leading limb vertical toe clearance, leading limb max toe elevation, and leading limb vertical heel clearance) autistic participants were likely not influenced by the illusion (41%, 47%, and 58% respectively).

Table 4.2. Mean group variability and within-group percentage of participants experiencing an illusory effect.

		Autism	Control	Mean Difference
Vertical Toe Clearance	Mean Variability	3.5cm	1.6cm	1.9cm*
	Within-group illusory effect	41%	75%*	
Max Toe Elevation	Mean Variability	3.9cm	1.2cm	2.7cm*
	Within-group illusory effect	47%	75%*	
Vertical Heel Clearance	Mean Variability	3cm	1.8cm	1.2cm*
	Within-group illusory effect	58%	92%*	

* single-samples t-test depicts significance at $p < 0.05$

4.4 Discussion

Everyday actions (e.g., walking) performed by autistic individuals show clear sensorimotor differences that often depict a clumsier motor performance (Jansiewicz et al., 2006), which is frequently more variable and portrays a less stable posture with increased lateral sway (Fournier et al., 2010b; Kohen-Raz et al., 1992; Molloy et al., 2003; Travers et al., 2013). It has been suggested that autistic differences to sensorimotor control occur due to altered integration of both sensory and motor information into the sensorimotor system (Gowen & Hamilton, 2013; Lidstone et al., 2021a). To examine the efficacy of visual integration into the autistic sensorimotor system, the present study utilised a simple and effective obstacle crossing protocol (as in Foster et al., 2016) that manipulated visual conditions by altering the face of the obstacle to be traversed. The nature of the autistic demographic in the present study required a creative manipulation to a straightforward everyday task (e.g., obstacle traversal, stepping) due to the sample requiring substantial or very substantial support (American Psychiatric Association (APA), 2013). Autistic demographics akin to those recruited for the present study are a vastly underrepresented population in the literature base and therefore empirical research with this population is incredibly valuable. This study provides a descriptive account of autistic gait and obstacle traversal with a discussion regarding sensorimotor integration processes that elicit replicated variability differences in autism.

As can be seen from the graphical interpretation of exemplar participant traces and confirmed by quantitative analyses of specific key markers of obstacle crossing (i.e., vertical toe clearance, max toe elevation, and vertical heel clearance of the leading limb), the autism group elicited greater variability than controls during

obstacle traversal. Graphical interpretation revealed that exemplar autistic participants show both greater variability than controls and greater variability within-group. These findings are consistent with literature documenting increased variability differences in both upper-limb (e.g., imitation, aiming) (Foster et al., 2020; Glazebrook et al., 2006), and lower-limb (e.g., locomotion) (Lum et al., 2021; Rinehart et al., 2006b), tasks in autism. It has been suggested that during traversal over raised surfaces, dangerous levels of clearance occur at approximately 0.5cm (Foster et al., 2014; Hamel et al., 2005), therefore, any significant increases to variability could place clearance into potentially dangerous levels, resulting in heightened risk of trips or falls.

During locomotion, autistic individuals show greater variability in stride length, less range of motion at the ankle joint and inconsistent walking 'smoothness' (Hallett et al., 1993; Lum et al., 2021; Rinehart et al., 2006b). It has been suggested that the autistic sensorimotor system has difficulty with the integration of visual, vestibular, and somatosensory inputs used to maintain postural stability (Molloy et al., 2003), which could then account for the inconsistent gait and stepping behaviour seen during locomotion and obstacle traversal (Gowen & Hamilton, 2013; Lum et al., 2021; Rinehart et al., 2006b). The present study sought to assess the efficacy of visual motor integration by manipulating the visual environment through the inclusion or omission of a horizontal-vertical visual illusion fixed to the face of the obstacle to be traversed. This relatively simple manipulation was decided upon based on previous experience conducting research with autistic participants who require substantial or very substantial support (American Psychiatric Association (APA), 2013). Simplifying both the task and the experimental manipulation facilitated successful adherence to the protocol and enabled access to underlying sensorimotor processes (i.e., integration processes) during obstacle traversal in an autistic sample that is vastly

underrepresented in the literature base and with whom the implications of investigations into autistic sensorimotor control would likely benefit most.

Although previous findings were not statistically replicated, it is likely that, given a greater sample size, control participants in the present chapter would have reflected the actions of those in previous work indicating that typically developing participants experience illusory effects that influence stepping behaviour when traversing small-height obstacles (e.g., stairs or steps) (Foster et al., 2015; Foster et al., 2016). Visual analyses of within-participant difference scores support this inference. For control participants, traversing over an obstacle with a horizontal-vertical visual illusion affixed to the face (or riser) successfully modulated sensorimotor control processes to elicit a raised toe clearance, max toe elevation, and heel elevation of the leading limb, above and beyond that of typical obstacle traversal (e.g., with no illusion present) (Foster et al., 2016). For older adults, navigating any changes in surface level (e.g., an uneven pavement, steps, staircases) can be a major cause of morbidity (Startzell et al., 2000), likely due to degraded vision in these demographics (Simoneau et al., 1991; Elliott et al., 2000), which then impacts the efficacy of integrating visual information into the sensorimotor system. Simple and cheap environmental manipulations, however, have been shown to elicit positive benefits to reduce the likelihood of trips and falls in such populations (Foster et al., 2015; Foster et al., 2016). With an optimised horizontal-visual illusion superimposed onto the face (riser) of a stair, older adults showed increased clearances during ascent (Foster et al., 2015), facilitating safer climbing of stairs, reducing the likelihood of accidents, trips or falls and promoting a safer living space. For typically developing participants, this horizontal-visual illusion influences the sensorimotor system to

perceive the obstacle or stair face as being taller, eliciting an increase in foot clearance over the obstacle (or onto the step) during traversal.

Autistic participants, on the other hand, showed no significant modulations to obstacle crossing whether an illusion was present or not. The lack of an illusory effect in the autism group may be due to autistic differences in illusion perception, which itself displays mixed findings (Happé et al., 1994; Hoy et al., 2004), or may also be due to autistic differences in the integration of visual information into the sensorimotor system (Dowd et al., 2012). In other words, the illusion may well have been perceived by the autism group, however, the autistic sensorimotor system may be less effective than controls to integrate this altered perception during locomotion. Research in control samples suggest that during gait performance, the online integration of visual information is crucial for adaptive locomotion success, particularly during the approach phase of obstacle crossing (Patla, 1998; Patla & Greig, 2006). Several processes crucial for successful locomotion and obstacle traversal, such as spatio-temporal gait parameters (Hallemans et al., 2009a), lower-limb kinematics (Hallemans et al., 2009b), inter-limb coordination (Hallemans & Aerts, 2009) and stability of the trunk (Moe-Nilssen et al., 2006), rely on vision, and are disrupted when visual information is no longer available. It is important to note that all participants in the present study demonstrated successful obstacle clearance on all experimental trials, indicating that visual information regarding the location, height and depth of the obstacle is available and was perceived during the experiment. Even when vision is available, autistic individuals experience alterations to both postural stability and gait (Molloy et al., 2003; Lum et al., 2021; Rinehart et al., 2006b), therefore indicating that the lack of illusory modulation for the autism group may be due to altered online integration of visual information (Lidstone et al., 2021a).

In summary, results indicate that although autistic participants did not modulate stepping behaviour when presented with illusory visual information, they did demonstrate considerable variability compared to controls across several dependent variables related to obstacle traversal. Together, these findings indicate the influence of altered online sensorimotor integrative processes in autism during visual control of action (Gowen & Hamilton, 2013). Although the illusory manipulation failed to elicit a significant leading limb foot clearance response in the autism group, there remains value in examining the influences of simple alterations to the supported-living environment. Using cheap but effective motor control protocols or environmental modifications in this way may provide a mechanism to provoke behaviour change (e.g., raising foot clearance over a step) that significantly reduces the likelihood of accidents, trips or falls, which have been successful in older populations (Foster et al., 2015). Being able to bring about behaviour change in this way may significantly relieve both the burden of worry on caregivers or support staff and reduce the need for emergency or first aid treatments by reducing the number of accidents that occur in supported-living environments for autistic individuals who require substantial or very substantial support. Additionally, examinations into crucial sensorimotor processes that underpin everyday actions (e.g., walking) may provide important knowledge to inform the development of motor control interventions, which may prove to be significant in preventing or keeping at bay increasingly more pronounced motor difficulties seen throughout autistic development through adolescence to adulthood (Travers et al., 2017).

5 Chapter Five: Epilogue

The focus of this thematic thesis was to conduct an examination into the autistic differences underlying sensorimotor planning, integration, and execution processes. This was demonstrated across three independent experimental chapters that assessed the underlying sensorimotor processes in distinct, novel tasks and provided in-depth kinematic analyses (see Figure 5.1 for overview of experimental design and summary of key findings). This epilogue will synthesise, summarise, and appraise key findings between chapters, and to the current motor control literature. Both theoretical and wider implications for motor control and autistic communities will be discussed with future directions recommended.

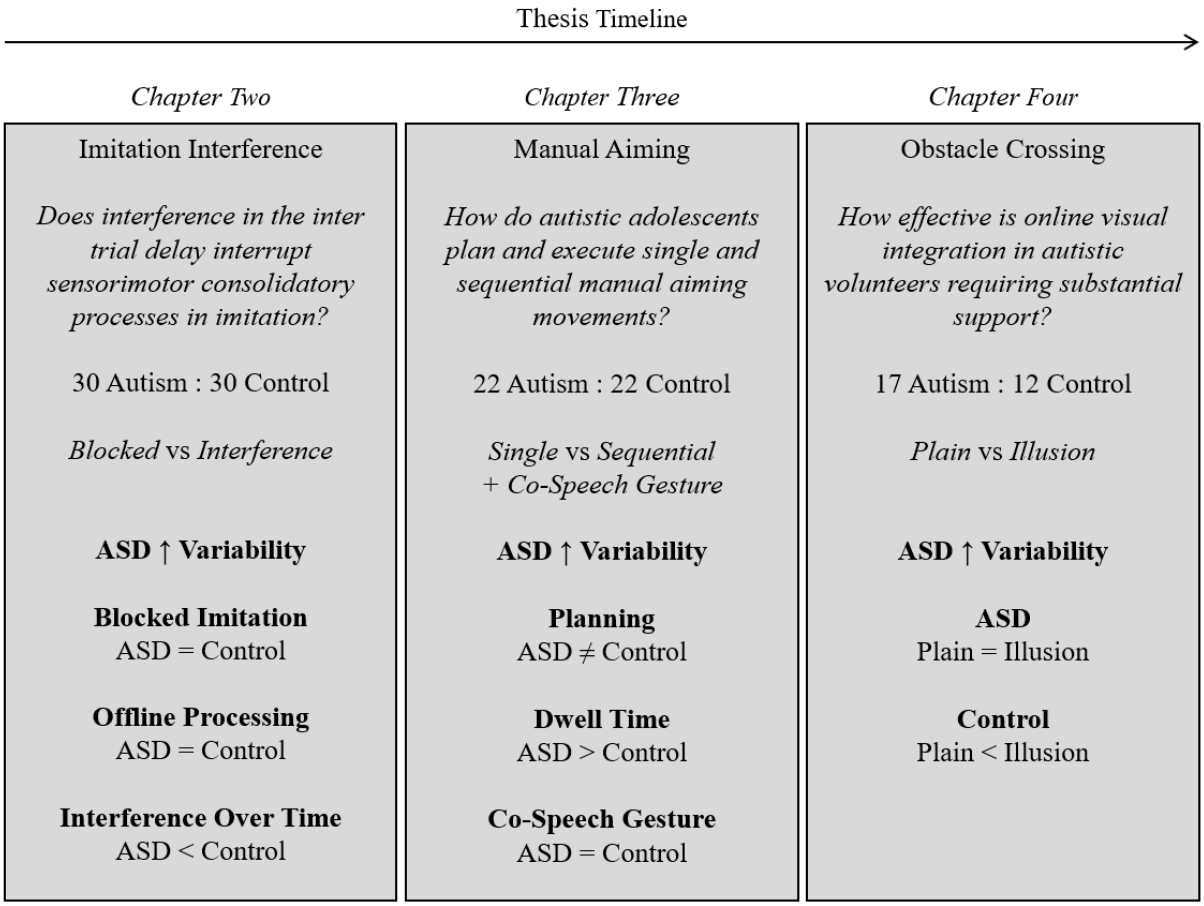

Figure 5.1: Overview of the experimental design and key findings of each chapter.

5.1 General Summary

An examination into the autistic differences underlying sensorimotor planning, integration, and execution processes, across three independent experimental protocols, will be presented and appraised with current and relevant motor control literature. The distinct protocols in the current programme of work: imitation in upper-limb motor control (chapter two), upper-limb single and two-segment manual aiming (chapter three) and stepping behaviour in obstacle crossing (chapter four), provide independent, yet related, examinations of underlying autistic sensorimotor behaviour compared to typically developing controls. In each experimental chapter (chapters two to four), autistic participants were matched (across age and gender) with typically developing control participants, with additional methods collected to provide additional demographic context. An overview of the experimental design and key findings can be seen in Figure 5.1. Overall, the current programme of work has both replicated, and extended, previous findings by developing and expanding current understanding of autistic sensorimotor control differences, across three distinct and novel experimental protocols. Details of each individual experimental chapter, along with a summary of findings, will be reported in the following chapter summaries.

Chapter Two

The initial aim of chapter two was to replicate findings (Foster et al., 2020) that autistic individuals can successfully imitate both typical (representative of everyday actions) and atypical (novel) biological motion kinematics displayed by a non-human agent model when the imitation environment is structured to facilitate trial-by-trial processing. Additionally, the central aim of chapter two was to conduct a

thorough kinematic examination of the sensorimotor processes underpinning adaptation, given that previous research (Hamilton, 2013; Nebel et al., 2015; Stewart et al., 2013) has suggested that autistic individuals show difficulty in representing biological motion to successfully imitate the actions of others. Chapter two adds new insight to the current autism motor control literature concerning the importance of offline sensorimotor consolidatory processing during repetitive imitation trials (i.e., during the inter-trial delay between trials *N* and *N+1*). In the interference condition, participants were required to perform a secondary motor task, drawing of concentric circles along a predetermined 'track' during the 4000ms delay between trials, in an attempt to examine offline consolidation and refinement of internal action models used to control voluntary imitation.

Firstly, percentage-time-to-peak-velocity, a key marker to identify the fidelity of biological motion imitation, occurred earlier when both autistic and control participants imitated an atypical model compared to a typical model. These findings replicate previous work (Foster et al., 2020b) indicting that the autistic sensorimotor system can represent the biological motion kinematics of novel (atypical) and representative (typical) actions when the imitation environment is structured so that imitation trials are presented in a blocked manner. Additionally, both autistic and control groups did not differ in response to the interference manipulation when mean data were examined, however, exploratory correlational analyses conducted on a key sensorimotor planning marker (peak acceleration) revealed that differences between the experimental groups become apparent as interference is implemented over time. Graphical interpretation revealed that for the autism group, no interference in the inter-trial delay led to a positive trial-to-trial correlation change for peak acceleration (△ 96%) across an experimental trial block. However, when interfering in the inter-trial

delay, autistic participants displayed a negative trial-to-trial correlation change for peak acceleration (△ -112%). Notably, no such pattern of effect occurred for the control group. This combination of findings indicates differences between the efficacy of the autistic and typically developing sensorimotor system during motor planning.

Chapter Three

The central aim of chapter three was to conduct a thorough kinematic analysis of single-segment and two-segment sequential manual aiming to examine whether there are autistic differences to upper-limb sensorimotor control and execution, and whether these differences are underpinned by altered sensorimotor planning (Foster et al., 2020; Glazebrook et al., 2008; Rinehart et al., 2006). A secondary aim was to provide insights on the effects of a co-speech gestures during instruction delivery on underlying sensorimotor control processes. It was hypothesised that the presence of a co-speech gesture, and the associated social nature of such an action, may modulate the autistic sensorimotor system (Happé, Cook & Bird, 2017; Wang & Hamilton, 2012) in a different way to controls given a fundamental part of the autistic diagnostic criteria centres around differences in social contexts (American Psychiatric Association, 2013; Silverman et al., 2010).

Compared to typically developing controls, autistic adolescents showed a motor performance advantage (e.g., significantly shorter movement times) when executing the initial movement segment in single and sequential aiming tasks. However, once total movement time was calculated (e.g., segment 1 + dwell + segment 2), no significant differences were observed in total movement time. The loss of the performance advantage gained during segment 1 was based on autistic adolescents spending almost double the time (128ms vs 69ms) at dwell (e.g.,

stationary between segments at the central target) than controls. It is proposed that autistic adolescents spent the additional time engaged in processes associated with feedforward and feedback-based processes needed to plan, control, and integrate sensorimotor information to perform the two segments that constrained the sequential aiming task. Notably, the data indicated significant autistic differences in kinematic markers (PA and PV) associated with the efficacy of feedforward planning and execution. These differences are likely due to processing and planning difficulties (Glazebrook et al., 2006, 2008, 2009; Mosconi et al., 2015; Nazarali et al., 2009; Wang et al., 2015; Zheng et al, 2019) related to specifying the required forces for movement execution that are controlled via internal action models during motor planning (Elliott et al., 2010; Wolpert et al., 1995). Importantly, the autism group, despite exhibiting greater spatial variability than controls throughout movement execution up to peak deceleration, showed a significant reduction (single segment = △ -59%; segment 1 of sequential = △ -48%; segment 2 of sequential = △ -25%) in variability from peak deceleration to movement endpoint that was proportional to the control group. This finding highlights that feedback-based control processes (Elliott & Allard, 1985; Khan et al., 2003) needed to adjust greater spatial variabilities earlier in the movement trajectory are both operational and effective in autism indicating that group differences in spatial variability are likely a by-product of altered sensorimotor planning in autism.

Moreover, adding verbal instructions via co-speech gestures to the task environment, a condition that was implemented to examine whether the underlying autistic sensorimotor processes would be modulated by a more-typical social environment (i.e., like in a classroom setting), did not significantly modulate the sensorimotor control and execution processes that underpinned manual aiming. Although social modulation in autism has been reported in joint attention (Dawson et

al., 2004) and imitation tasks (Nebel et al., 2016) that require a performer to interact and process information from a human agent (Lidstone et al., 2021b), results from chapter three suggest that disruptions to the processing of social information in autism is not necessarily pervasive across all contexts. The protocol utilised was more directly related to current teaching practices whereby a teaching assistant (TA) or teacher will often sit alongside a pupil and utilise gesture to accompany verbal instruction and yielded no significant alterations to autistic sensorimotor control. This finding provides scope for future research to examine how best to implement sensorimotor control interventions in a classroom and how to support the teaching practices of autistic pupils.

Chapter Four

The central aim of chapter four was to examine the integration efficacy of visual information into the autistic sensorimotor system, utilising a simple, but effective obstacle crossing protocol that manipulated visual conditions. Autistic adults were required to walk along the predetermined (8m approx.) walkway at a self-paced speed, step over a mid-walkway obstacle with their preferred leading-limb and resume walking to the end of the path. Experimental manipulations to the appearance of the mid-walkway obstacle created the experimental conditions. The use of the horizontal-visual illusion (as in Foster et al., 2016) provided a creative and alternative method (than previous chapters) to examine online visual integration into the sensorimotor system in autistic adults that required substantial and/or very substantial social support and are vastly underrepresented in the literature base (American Psychiatric Association (APA), 2013). This exploratory chapter also provides a descriptive account of autistic gait and obstacle traversal with a discussion regarding sensorimotor

integration processes that also showed significant differences in key dependant variables pertaining to obstacle traversal in autism.

Chapter four replicated previous work indicating that typically developing participants experienced visual illusory effects that influenced stepping behaviour when traversing small-height obstacles (e.g., stairs or steps) (Foster et al., 2015; Foster et al., 2016). The visual illusion led to a significant increase in toe clearance, max toe elevation, and heel elevation of the leading limb occurring in illusion trials, compared to the no-illusion trials. On the other hand, autistic participants showed no significant illusory modulations to stepping behaviour when locomoting to, and traversing over, the mid-walkway obstacle. The lack of an illusory effect may be due to autistic differences in visual illusion perception (Happé et al., 1994; Hoy et al., 2004) or could be due to autistic differences in the integration of visual information (Dowd et al., 2012) into the sensorimotor system for action. An exploratory, graphical interpretation of stepping behaviour revealed that exemplar autistic adults showed both greater variability than controls, and greater variability within-group. These variability differences suggest altered sensorimotor planning and online sensorimotor integrative processes involving the use of vision during action (Glazebrook et al., 2009; Gowen & Hamilton, 2013; Wang et al., 2015), which may have been exacerbated (Hannant et al., 2016a; Nebel et al., 2016) in the autistic adults given they required substantial or very substantial support to perform everyday activities.

The individual experimental chapters contained within this thesis (overview in Figure 5.1; also explained in the above subsections) independently provide additional clarity to the current understanding of sensorimotor planning, integration, and execution processes in autism across various contexts and/or demographics. Importantly, when considered both in conjunction and in relation to current literature,

several interesting themes arise that will be discussed and appraised in the subsequent sections of this thematic thesis.

5.2 Sensorimotor Processing in Autism

Sensorimotor Planning and Feedforward Control

Prior to initiating a motor action, and throughout the initial stages of execution of that action, feedforward sensorimotor planning processes control the efficacy of movement preparation and early execution (Elliott et al., 2010; Miall & Wolpert, 1996). Results from chapters two and three indicate altered sensorimotor planning processes in autism, whereby feedforward control mechanisms are operational yet appear to function differently in autistic vs typically developing control groups.

Motor timing data from chapter two replicated previous work suggesting the imitation of biological kinematics presented by a non-human agent model was successful for autistic participants (Foster et al., 2020b). Percentage-time-to-peak-velocity (PTTPV) occurred earlier for both autistic and control participants when imitating atypical stimuli compared to typical stimuli (the atypical model presented a PTTPV of 18% compared to 44% presented in the typical model). Previously, autistic participants were found to have difficulty in representing the kinematic differences of a novel, atypical model during imitation (Hayes et al., 2016). The atypical and typical models, however, were displayed in a randomised trial order (Hayes et al., 2016), whereas in chapter two (and in Foster et al., 2020b) each model was presented independently in repetitive blocked trial structures. Potentially, when trials are structured in a blocked manner (opposed to random trial orders), sensorimotor planning processes are facilitated (Li & Wright, 2000; Simon & Bjork, 2001) by

reducing the requirement of the sensorimotor system to construct, deconstruct, and reconstruct sensorimotor representations (i.e., internal action models) for each individual trial (e.g., trial *N* vs trial *N+1*) (Cross et al., 2007). Thus, implementing a structured and predictable environment that facilitates trial-by-trial processing is suggested to allow the autistic sensorimotor system to utilise advanced and expected trial information to assist and support sensorimotor planning processes for the upcoming trial.

Despite the ability to facilitate autistic sensorimotor planning processes via predictable trial blocks, timing data from chapter three revealed that when multiple actions (i.e., segments) are combined in sequence, autistic participants exhibited a different approach than typically developing peers. Importantly, compared to controls, autistic adolescents executed the initial movement segment significantly faster than controls across both single and sequential aiming conditions, with no significant differences present between the two conditions. Following the initial movement segment, however, autistic participants spent almost double the time at dwell before completing segment 2, which suggests that the autism group are approaching sequential aiming tasks in the same way as the single aiming tasks (Fabbi-Destro et al., 2009), disregarding the need to effectively plan for the second segment until terminating segment 1. This has been shown previously, for example, when tasks require an object to be picked up followed by an additional movement segment to place that object into a container, typically developing children display elongated movement timing in both segments (i.e., the reach, and the place phases) when the total movement requires greater precision (i.e., the object is placed into a smaller container). On the other hand, autistic children did not appear to modulate the timing of the initial reach phase, and only display elongated movement timing in the second

segment, when greater precision is required. This pattern of findings indicates that autistic children, like those in chapter three, may approach each segment of sequential actions (i.e., actions with two segments) independently, rather than as one complete action, unlike the typically developing children who appear to modulate and plan both segments according to total task difficulty (Fabbri-Destro et al., 2009). Interestingly, in chapter three when overall movement time was calculated (i.e., segment 1 + dwell + segment 2), no significant overall timing differences between autism and control groups were present. These findings highlight that even though the autism group completed segment 1 faster and spent almost double the time stationary between segments than controls, they completed entire sequential aiming trials in overall timing that was not significantly different. The extended dwell periods likely incorporate the processing of the terminal feedback of segment 1 and the initiation of the sensorimotor planning of segment 2 (Adam et al., 1995). Notably, the dwell time of autistic participants (128ms) was still less than a typical movement onset latency (e.g., reaction time) to the first segment of a sequential aiming task (e.g., 220-241ms, Rand et al., 1997), thus indicating that predictive sensorimotor processes may have been used to facilitate the transition between the first and second segment (Rand, 2018). It is important to note that for the control group, additional feedforward sensorimotor processing occurred, whereby spatial variability of peak acceleration during segment 2 of the sequential aiming task was significantly lower than spatial variability of peak acceleration in the preceding segment (e.g., segment 1). The implication of this finding, in appraisal with the motor timing data (both individual segment and dwell timing), indicates that sensorimotor processes for the control group elicited a carry-over effect to facilitate the planning of the subsequent movement segment, whereas this did not appear to occur for the autism group. The increases in dwell time on

sequential manual aiming trials for the autism group may well be the result, in part, of sensorimotor planning of the upcoming movement segment.

Kinematic data, when accompanying the timing data, provided important details that can further describe and explain motor execution and can illuminate underlying sensorimotor processes. Being able to deconstruct motor behaviour to the kinematic level details the sensorimotor differences between autistic and typically developing controls. In chapter three, and compared to controls, the autism group exhibited greater magnitudes of peak acceleration with greater intra-participant variability in the magnitude of both peak acceleration and peak velocity. Greater spatial variabilities were also present at peak acceleration (in only the second segment of sequential aiming) and peak velocity. Autistic participants in chapter two also demonstrated greater spatial variabilities at peak acceleration and peak velocity. According to the multiple process model of goal-directed aiming and reaching (Elliott et al., 2010, 2017), alterations to early kinematic markers (i.e., peak acceleration and peak velocity) are more indicative of alterations to feedforward sensorimotor planning processes, than feedback sensorimotor integrative processes (Khan et al., 2003; Miall & Wolpert, 1996). Altered sensorimotor planning processes in autism have been examined previously (Glazebrook et al., 2008; Nazarali et al., 2009). For example, a multiple-experiment examination of manual aiming revealed that when advance information was directly available (i.e., target location), the autistic participants demonstrated a pattern of performance (i.e., reaction and movement timing) not significantly different to controls. However, once advance information was no longer direct, and required environmental inference (i.e., visual perception from the testing environment), autistic participants did not appear to attempt to use anticipatory strategies to plan and perform a more efficient or effective movement (unlike

controls), and instead defaulted to a central starting position (Glazebrook et al., 2008). Moreover, alterations to either the target location or limb to be used, following planning and preparation of a manual aiming movement, resulted in more pronounced increases to reaction and movement times for the autism group (although both groups did show increases) (Nazarali et al., 2009). The implication is that the ability to extract task relevant information, which ultimately underpins the efficacy of sensorimotor planning (Foster et al., 2020a; Glazebrook et al., 2006, 2009; Wang et al., 2015), is likely altered in autism. More specifically, less efficient sensorimotor planning is suggested to be due to a difficulty in the specification of magnitude and the timing of specific muscular forces to initiate execution (Elliott et al., 2010; Mosconi et al., 2015; Wolpert et al., 1995), which can be demonstrated by examining changes in early kinematic markers.

Before movement initiation, sensorimotor planning processes form internal action models (i.e., sensorimotor representations of the upcoming movement) containing expected sensorimotor efferent (i.e., motor signals to relevant musculature) and afferent (i.e., sensory consequences) signals based upon prior experience (Wolpert et al., 1995, 1998, 2011). These internal action models provide a framework for subsequent motor execution and enable sensorimotor planning processes to control both the specification of magnitude and timing of muscular forces required to initiate the upcoming movement. For example, in a grip force task requiring participants to generate a target force by squeezing the thumb and index finger onto opposing load cells, autistic individuals produced less accurate initial force contractions than controls, which were accompanied by greater peak force rates and larger overshoots (Mosconi et al., 2015). Autistic individuals also showed greater variability when striving to sustain a specific target force, with an increased reliance on slower

feedback-based mechanisms, compared to faster feedforward predictive mechanisms (David et al., 2009; Mosconi et al., 2015). Prior to peak acceleration, execution is primarily influenced by the efficacy of the internal action model and the component efferent and afferent expectations (Miall & Wolpert, 1998; Elliott et al., 2010, 2017). Therefore, it is likely that autistic participants exhibited differing responses in early kinematic markers compared to typically developing controls (Foster et al., 2020a; Glazebrook et al., 2006) because they had trouble specifying the required forces for movement execution (Mosconi et al., 2015; Wang et al., 2015) while forming internal action models (Wolpert et al., 1995) during motor planning (Elliott et al., 2010).

In chapter two, an exploratory, correlational analysis of peak acceleration between trial *N* and trial *N+1* was conducted to further examine sensorimotor planning processes involved in voluntary imitation. Interestingly, the correlational analysis revealed a 3-way interaction between group (i.e., autism and control), task (i.e., no interference and interference) and phase (i.e., early, and late). The control group showed no significant trial-to-trial differences across practice for either task condition. Post-hoc analyses revealed that the autism group, however, exhibited a significantly stronger trial-to-trial correlation when imitating without, rather than with, interference in the late phase. Graphical interpretation revealed that for the autism group, as practice progressed, no interference in the inter-trial delay led to a positive trial-to-trial correlation change (△ 96%) for peak acceleration. Moreover, interference in the inter-trial delay led to a negative trial-to-trial correlation change (△ -112%) for peak acceleration. Previous work suggests that repetitive Transcranial Magnetic Stimulation (rTMS) applied to the primary motor cortex (M1) during the inter-trial interval of observational practice trials, where participants performed upper-limb actions of a robotic manipulandum against varying force fields, appeared to interrupt

consolidatory sensorimotor processes (Brown et al., 2009). Results of chapter two, and those of previous work (Brown et al., 2009), indicate that post execution (i.e., in the inter-trial delay) consolidatory sensorimotor processes are important to facilitate trial-to-trial motor learning and adaptation as a trial block progresses (McGregor & Gribble, 2017), particularly for autistic participants. Potentially, for autistic participants, the combined impact of interference occurring during the inter-trial delay, throughout an experimental block of 40 trials, disrupted crucial sensorimotor processes from efficiently refining and updating the internal action model representing the imitation task (opposed to the secondary motor task) to support the planning of the upcoming imitation trial. This constraint on the autistic sensorimotor system may be due to a lack of available resources to process both the secondary-motor task and the internal action model of the upcoming movement, reducing the effectiveness of either. During blocked practice with no interference, autistic participants benefitted from the predictable and fixed trial order, allowing sensorimotor planning and integration processes to facilitate the construction and continued refinement of internal action models (e.g., the imitation task). On the other hand, when subject to motor interference in the inter-trial delay it could be that the sensorimotor system, when attempting to construct and refine an internal action model to support imitation during motor planning (Cross et al., 2007), is overridden by resources being allocated to process the secondary motor task. The combination of findings elicited by the manipulations in chapter two indicate the importance of inter-trial processing in blocked practice structures for sensorimotor learning and consolidatory processes in autism.

Sensorimotor Integration and Feedback Control

As a movement progresses beyond peak acceleration towards movement endpoint there is increasing opportunity for the movement trajectory to be corrected by integrating additional sensory information (e.g., visual, and proprioceptive) into the sensorimotor system (Elliott et al., 2001; Heath et at., 1998; Khan et al., 2003; Starkes et al., 2002). Chapters two, three and four demonstrate distinct group differences throughout a movement trajectory, whereby the autism group is more variable across several dependant variables. These findings implicate sensorimotor integrative and feedback control processes, alongside the previously discussed feedforward control processes, across multiple tasks.

In chapter two, significant group differences occur in the spatial variability of key kinematic markers [i.e., peak acceleration (PA), peak velocity (PV) and peak deceleration (PD)], with autistic participants remaining more variable than controls at each kinematic marker throughout the entire movement profile, up to and including movement endpoint. Comparable spatial variability findings were also evident in chapter three, with autistic variability differences in early kinematic markers still evident across the movement trajectory and at the endpoint of each movement segment. It is important to note that the protocols recruited in chapters two and three are distinct, with further differences between volunteer demographics (i.e., mean age approx. 22 years in chapter two; mean age approx. 14 years in chapter three). Chapter two required voluntary imitation guided by an external model depicting specific biological motion kinematics to be imitated, whereas chapter three was a manual aiming movement that required placing an object onto a specific target (or targets) as determined by task instruction. Additionally, significant variability differences were also present in chapter four, with graphical interpretations and quantitative analyses

of specific key landmarks throughout the obstacle crossing swing phase (i.e., vertical toe clearance, max toe elevation, and vertical heel clearance of the leading limb), displaying autistic participants as being significantly more variable than controls. The chapters in this thesis demonstrate consistent group differences whereby the autism group is significantly more variable than typically developing controls, across protocols, contexts and demographics that fundamentally differ (i.e., in populations of young adults and adolescents).

Throughout the early stages of a movement trajectory, once feedforward planning processes have facilitated the initial force-production to drive execution and a movement has initiated (Wang et al., 2015), sensorimotor integrative processes can utilise feedback (e.g., visual, and proprioceptive) from sensory systems to make significant alterations to control the movement (Khan et al., 2003). For example, when the spatial location of a target was unexpectedly altered and moved to a new location during rapid aiming actions, visual information was integrated online to modify movement trajectory to adjust to the new target location (Heath et al., 1998). Additionally, a further examination of visual integration revealed that typically as movement times become longer (e.g., a movement takes more time), vision becomes more influential in reducing variability as the movement progresses (e.g., at later kinematic markers) (Khan et al., 2003), whereas at shorter movement times sufficient time is likely not available to utilise vision to correct or alter the movement trajectory adequately (Starkes et al., 2002). Also, vision is likely to be relied upon for online adjustments to the movement trajectory when it is predictably and reliably available (Elliott & Allard, 1985). However, in chapter four no illusory effects occurred for the autism group, whereas the control group displayed a typical response (Foster et al., 2015; 2016) to a horizontal-vertical visual illusion being superimposed to the face of

a to-be-traversed obstacle. Visual information from the obstacle (i.e., location, height, depth, and width) must have been perceived and processed by both the control and the autism groups, as during the experiment the obstacle was traversed successfully on 100% of trials. It may be the case that the additional visual stimuli (i.e., the horizontal-vertical visual illusion) was not integrated effectively into the autistic sensorimotor system during locomotion and obstacle traversal. For example, previous work suggests that during performance of manual aiming actions with and without vision, both autism and control groups take longer to execute actions when vision was available, but autistic participants display a greater increase between no-vision and vision conditions (Glazebrook et al., 2006). Additionally, performance of a point-to-point movement task also outlined autistic differences to the integration of visual information in the immediate environment (Dowd et al., 2012). Autism specific differences to motor performance were apparent in the presence of a visual distractor, whereby typical children modulated their movement to account for all available environmental cues (i.e., the visual distractor), yet the autism group displayed no significant modulation (Dowd et al., 2012). It is likely that typically developing participants (both the control groups in Dowd et al., 2012, and in chapter four of the present thesis), unlike autistic participants, processed and integrated available visual information effectively and typically, resulting in sensorimotor integrative processes facilitating modulations to subsequent motor performance. It has been previously reported that specific differences in sensorimotor integration may be due to an autistic specificity in the prioritisation of proprioceptive, over visual, information (Haswell et al., 2009). During a motor learning experiment participants were required to manipulate a robotic arm that produced differing velocity-dependent curl force fields which perturbed motion. Patterns of generalisation in the autism group revealed a

stronger than typical reliance on proprioception (Haswell et al., 2009), which implicated altered sensorimotor processing and integration of visual information in autism compared to controls. These differences to sensorimotor integration may indeed be exacerbated (Hannant et al., 2016a; Nebel et al., 2016) for the autistic sample of participants in chapter four, given they required substantial or very substantial support to perform everyday activities.

The fact that significant group variability differences were recorded across entire movement profiles, and across multiple experimental protocols (chapters two, three and four), suggests that both feedforward and feedback sensorimotor processes are altered in autism. Importantly however, despite exhibiting greater spatial variability than controls, autistic participants made significant attempts to reduce spatial variability towards movement endpoint and to correct for early increases in spatial variability. In chapters two and three, spatial variability at movement endpoint (of both the first and second segments in chapter three), was smaller than spatial variability at peak velocity and peak deceleration, for both autistic and typically developing participants. This pattern of autistic sensorimotor control has also been documented in other goal-directed manual aiming tasks, notably in a task requiring participants to move their dominant index finger to one of two target buttons indicated by a light-emitting diode following a random fore-period. Specifically, like chapters two and three, both autistic and control participants successfully reduced spatial variability at peak deceleration by movement termination upon reaching the target (Glazebrook et al., 2006). Importantly, the attempts to correct for greater early spatial variability across chapters two and three were in magnitudes of change proportional, and not significantly different to controls. This significant proportional (relative to controls) reduction in spatial variability towards movement endpoint indicates the

successful use of online feedback control processes to adjust the movement trajectory in autism (Desmurget & Grafton, 2000; Elliott et al., 1991; Heath et al., 1998; Khan et al., 2003). Significant sensorimotor adaptation effects, for both autism and control groups, were also present in a motor aiming task containing perturbation to the visuomotor relationship between the participant and the target location (Gidley Larson et al., 2008). More specifically, when a prism perturbed the location of a target (via wearing of prism goggles), autistic participants demonstrated patterns of adaptation, and skewed post-adaptation after-effects, not significantly different to controls (Gidley Larson et al., 2008), This pattern of effects was also found in a task requiring participants to maintain wrist location when caching balls of various weights (Mostofsky et al., 2004). Further research also substantiated these effects, whereby forcefield-manipulated control of a robotic arm elicited typical adaptation and post-adaptation washout effects for both the autism and control groups (Gidley Larson et al., 2008). Taken together, these findings support that sensorimotor feedback corrective and adaptation processes are indeed operational in autism. However, although the autistic participants in chapters two and three were able to reduce spatial variability towards movement endpoint by utilising sensorimotor feedback processes to make online corrective adjustments, significant group differences remained. This implies that the operational and effective feedback control processes (Gidley Larson et al., 2008; Mostofsky et al., 2004) were not sufficient to overcome the altered feedforward sensorimotor planning processes affecting the preparation and initial stages of motor execution depicted in autistic sensorimotor control.

5.3 Social Modulation in Autism

Across chapters two and three, participants were required to process aspects of social information. In chapter two, although the to-be-imitated models displayed no social characteristics related to human form (i.e., the dot itself was not human in appearance), the point-light dots (Johansson, 1973) displayed biological motion kinematics that described the human action (Kozlowski & Cutting, 1977). In chapter three, an experimental manipulation was introduced to examine whether the underlying sensorimotor processes were modulated by the presence of co-speech gestures that accompanied the verbal instructions. This manipulation was implemented due to autistic diagnostic criteria being heavily centred around social interaction, primarily "deficits in nonverbal communicative behaviours used for social interaction, ranging, for example, from poorly integrated verbal and nonverbal communication; to abnormalities in eye contact and body language or deficits in understanding and use of gestures; to a total lack of facial expressions and nonverbal communication", as portrayed in the DSM-5 (American Psychological Association, 2013). It was hypothesised, that by integrating co-speech gestures to accompany verbal speech during instruction delivery, the autistic sensorimotor system would be significantly modulated and as a result produce differing movement profiles between co-speech gesture and no co-speech gesture experimental conditions.

The findings from chapter two demonstrate that the autistic sensorimotor system could effectively imitate both atypical (novel) and typical (representative) biological motion kinematics presented via a point-light dot and were not significantly impacted by the presentation of kinematics that were human in nature. The social top-down response model (STORM; Wang & Hamilton, 2012) provides a basis for

understanding the control of social modulations, specifically for imitation. STORM suggests that the main factor to modulate imitation is the presence of a social model (e.g., the form of a person). The imitator would likely observe facial areas of a model, as well as other areas determined to be significant in the successful imitation of that model (e.g., the configuration of the limbs), and would mimic to maximise any potential social advantage (e.g., to build rapport) (Wang & Hamilton, 2012). As such, direct gaze during a stimulus-response compatibility (SRC) protocol elicited a stronger social modulation effect for control participants, whereby congruent hand actions were performed significantly faster when preceded by direct gaze, compared to averted gaze. This pattern of effect was not seen for autistic participants, who did successfully mimic, but did not show a specific enhancement of social modulation (Forbes et al., 2017).

Importantly, in chapter three, when co-speech gestures accompanied verbal instruction there did not appear to be any meaningful modulation to underlying sensorimotor processes involved with manual aiming performance. Previous work suggests that autistic participants are slower to fixate to a correct target once co-speech gestures were implemented, potentially indicating slowed cross-modal processing (Silverman et al., 2010). Specific autistic differences in a task requiring pure motor imitation of a human agent performing various actions were also found (Lidstone et al., 2021b). Although clear autism specific differences are present across social orienting and joint attention (Dawson et al., 2004), involving the coordination of attention to a common referent (i.e., target/s) (Mundy, 2018), following the referential gaze (Vivanti et al., 2017), and imitating or mimicking the actions of another person (Forbes et al., 2017; Lidstone et al., 2021b), when appraised alongside the findings of chapters two and three it is likely that the reported social integrative deficits in autism

are not conclusively pervasive across contexts. These social processing and integrative differences may well be disrupted in the pure imitation of the actions displayed by a human agent (Lidstone et al., 2021b), but did not appear to be impacted across imitation of a non-human agent model depicting biological motion (chapter two; Foster et al., 2020b) and in manual aiming when co-speech gestures accompanied verbal speech during instruction delivery, when those gestures were executed by a human agent (chapter three), which may be in part due to the degree of task complexity. It is important to note that chapter three was also more directly related to some current teaching practices whereby a teaching assistant (TA) or teacher will often sit alongside a pupil and utilise gesture to accompany verbal instruction in a classroom environment. This combination of findings warrants further investigation and examination to determine where context-specific differences to the processing of social information and underlying sensorimotor modulation occur in autism, with a view to inform teaching practices and facilitate the development of classroom-based interventions to support autistic pupil learning and attainment in educational environments and beyond (Cook et al., 2013; Kelly et al., 2008).

5.4 Wider Considerations and Limitations

Participatory Research

The current landscape of research in autism appears to be evolving to shape meaningful participation and collaboration between researchers and participants. Participatory research involves fostering the relationship between research teams and participants to strive to ensure participation in research protocols meets the needs of not only the researchers, but more importantly, the needs of autistic participants and

their networks. Although participatory research (as a specific formal approach) is relatively young, non-formal approaches of this nature have been ongoing for some time between research groups and their autistic participants and are deemed to be a very beneficial and valuable for all involved (Keating, 2021). Several topics have been regarded as important to create a successful participatory research community: "Respect, Authenticity, Assumptions, Infrastructure and Empathy" (Fletcher-Watson et al., 2019).

During the process of completing this programme of research many fundamental principles of the participatory research approach to collaboration between researchers and autistic participants (and their networks) were followed. For example, several research meetings took place during early planning stages to ensure that the autistic voice was represented in all aspects of research, such as study aims, objectives, suitable and appropriate methodology, and language used to deliver instructions. The research team engaged in several group meetings with a selection of previous autistic participants who were interested in becoming more involved in the research process, these participants later became autistic advocates. Having been participants previously, the autistic advocates were familiar with our area of work and were happy to engage in a collaborative discussion to not only identify important and interesting areas of further research, but also to assist in creating and shaping future experimental protocols. Extensive discussion and pilot testing, with both our autistic advocates, Special Educational Needs Co-ordinators (SENCOs) at our partner schools, and the Activity Manager at our partner autism charity resulted in significant changes to initially proposed experimental protocols across each chapter in this programme of work. These co-creation meetings were fundamental to ensure that protocols were rigorous, that correct and accurate data was collected, and to promote adherence to the

protocol by ensuring appropriateness of the tasks for the autistic volunteer sample. Additionally, prior to data collection beginning, a period of familiarisation was implemented to facilitate the smooth running of the programme of research in all settings (schools, autism charity day sessions). As such, time was spent assisting in classes and sessions acting as a teaching assistant (TA), this process allowed all children to become familiar with the researcher and the researcher to become more familiar with how classes and sessions are structured, as well as organisational structure. By engaging in this process, valuable information was attained to inform the creation and operation of experimental protocols that reduce situational and attentional noise (e.g., selecting a suitable testing location, removing distracting objects such as computer screens) to create ecologically valid experimental testing environments and protocols. For example, in chapter three the manual aiming protocol is directly adapted from a Speech and Language Therapy (SALT) learning resource task the children engaged in on a regular basis. Adapting a familiar task facilitated adherence and understanding to the experimental protocol. Following data collection, processing and interpretation, several feedback sessions were conducted with both autistic advocates, SENCOs, autism charity partners and participants. These sessions were to provide post-participation clarification of the results attained and to hear thoughts from the wider research network on the interpretations made. These feedback and plenary sessions were hugely valuable for all and allowed a cyclical approach to research collaboration and participation to be established.

Diagnosis

Although differences to underlying sensorimotor processes are not currently classified as one of the core characteristics of autism (as per the DSM-V), autistic

individuals indeed show clear and observable sensorimotor differences when compared to typically developing peers (Kaur et al., 2018; Marko et al., 2015; Mostofsky & Ewen, 2011). Sensorimotor processing differences may well be the precursor to the objective, observable movement differences, including delays to the onsets of significant motor milestones (e.g., lying, righting, sitting, and crawling) documented during autistic development (Teitelbaum et al., 1998). These sensorimotor control differences have been shown to correlate with severity of autism and may contribute to an autism-specific disruption in the perception of others, potentially underpinned by developmental lived experience with an atypical movement profile (Cook et al., 2003). It has also been suggested that autistic individuals exhibit a greater reliance on proprioceptive feedback, over visual, which is also indicative of greater disruptions to social functioning (Haswell et al., 2009).

The current thesis has demonstrated across multiple contexts that underlying sensorimotor processes can be accessed, quantified, and examined consistently and accurately. Therefore, it may be possible that examinations at the kinematic level can yield exciting promise to further understand and evidence autistic differences to sensorimotor control that can elucidate autistic development and assist in earlier autism diagnosis. The average age of an autism diagnosis between 2012 and 2019 was suggested to be approximately 60.48 months (5.04 years) and 43.18 months (3.59 years; only including children aged $\leqslant$10 years) (van't Hof et al., 2021). However, it may be possible to utilise simple yet effective (and data rich) protocols, such as in the current thesis, to access and examine the underlying sensorimotor processes at the kinematic level in children much younger than the average age for diagnosis. If a definitive, or suggestive, kinematic profile for autistic sensorimotor control could be identified, it may facilitate the diagnostic process beginning earlier, which may equal

earlier support and diagnosis for children deemed as potentially likely to later gain an autism diagnosis (Cavallo et al., 2021).

Intervention

In the same vein as the above section, it may be possible, and potentially vital, to utilise our understanding of the sensorimotor system (and how the underlying mechanisms operate in autism) to create activities which intervene and foster the effective development of motor abilities, which may in turn impact the altered developmental trajectory of social skills in autism. An extensive body of work (by no means exhaustive; Foster et al., 2018, 2020a, 2020b; Glazebrook et al., 2006, 2008; Hayes et al., 2016; 2018), underpinned by a multiple-process model of goal-directed limb control (Elliott et al., 2010, 2017, 2020), has been dedicated to examining these autistic differences in sensorimotor control. Understanding these differences to underlying sensorimotor processes could provide valuable evidence to inform the creation of interventions aiming to provide support during autistic development (Cavallo et al., 2021). Lloyd et al., (2011) suggest that clinical, educational, and support networks of autistic children should strive to promote play consisting of gross and fine motor skills and widen the scope of early intervention from a focus primarily on communication and behaviour. Assessments and interventions that target fine and gross motor skills may well have knock-on effects on other areas, such as a reduction in isolation from social interactions with classmates, which may follow a decline in motor competency (Lloyd et al., 2011). It is important to strive to explore and improve methodological standards for the types of future research studies or areas likely to inform the development of suitable behavioural interventions: (i) feasibility studies, (ii) mechanistic studies, (iii) efficacy studies, (iv) effectiveness studies, with each

having distinct goals (Green et al., 2019). The goal of a feasibility study is to determine the viability of a protocol, such as practical and economic considerations. Mechanistic studies demonstrate that the behavioural interventions or protocols target the correct and desirable mechanisms of processing. Efficacy studies are used to validate those behavioural interventions as the cause of any modulations, beyond no intervention. Once validated, effectiveness studies determine whether the behavioural intervention produces the desired result in a real-world setting, often in less-controlled settings than efficacy studies (Green et al., 2019). The current programme of work has demonstrated that simple and effective protocols are both feasible (i) and access specific sensorimotor processing mechanisms (ii). The next steps would be to extend the protocols in the current programme of work to potentially target specific behavioural improvements (e.g., educational attainment, handwriting, mathematics). Implementing and using simple, but effective, motor control protocols to inform the development of classroom-based interventions could provide a mechanism to facilitate autistic personal and educational attainment in the future. This may then prove to be significant in preventing or keeping at bay increasingly more pronounced motor difficulties seen throughout autistic development through adolescence to adulthood (Travers et al., 2017).

Limitations

Throughout the latter stages of data collection for this thesis, the global SARS-CoV-2 (COVID-19) pandemic took hold in the UK and immediately halted in-person attendance at several testing location due to government-imposed restrictions, which caused several alterations or adaptations to be made. Chapter two remained unaffected. Chapter three required an adaptation to the measures used in quantifying

autism severity to be made (i.e., due to the sensitivity and subtlety of the ADOS-2 assessment it was not feasible to pursue online collection of this measure, therefore the SRS-2 questionnaire was conducted online). Chapter four was most impacted by this interruption, and as such, data collection for the initial experimental task fell below the expected *N*, and the planned secondary experimental task could not be conducted (note: ethical approval for this task was attained). This task was developed to firstly examine whether autistic individuals succumb to the visual illusion manipulation in an isolated setting (i.e., not occurring during physical action). The plan was that this additional measure would complement the behavioural obstacle crossing data and provide more clarity and insight into sensorimotor planning and execution processes occurring in autism.

5.5 Concluding Remarks

Summary of Thesis

This thematic thesis sought to examine autistic differences to underlying sensorimotor processes pertaining to planning, integration, and execution. Three independent empirical chapters (chapters two, three, and four) implemented novel and creative methodologies to access specific sensorimotor mechanisms, guided by an extensive body of work demonstrating unambiguous access to feedforward and feedback control mechanisms (Foster et al., 2018; Foster et al., 2020a; Foster et al., 2020b; Hayes et al., 2018). Inferences reached following conclusion of the current programme of work, via synthesis and appraisal with current literature, indicate clear autistic differences to both feedforward and feedback control across both upper-limb and lower-limb tasks. This thesis proposed the potential for utilising the direct and

explicit access to the underlying autistic sensorimotor control system, via simple and effective protocols, to seek to enhance capability of both diagnosis and intervention practices in the future. Thus, by both facilitating capability for earlier diagnosis, and by enabling development of more effective intervention techniques, improved support for autistic individuals and their families is a likely consequence.

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