SENSORIMOTOR LEARNING AND CONTROL IN AUTISM SPECTRUM DISORDERS: THE ROLE OF SENSORIMOTOR INTEGRATION

NATHAN CHARLES FOSTER

A thesis submitted in partial fulfilment of the requirements of Liverpool John Moores University for the degree of Doctor of Philosophy

October, 2018

Contents

I Acknowledgements

My journey through higher education has not been a straight forward one, there have been many twists and turns along the way and what seemed to be ever changing goal posts. I would therefore like to take this opportunity to show my appreciation for those who have guided and aided me throughout. Firstly, my supervisory team. To my director of studies Dr. Spencer Hayes, I will be eternally grateful for the opportunity you provided me and the 'pressure' you applied to make sure I reached the correct decision. Thank you for your continued dedication and support, in not only our combined scientific interests but outside of the lab as well. To my second supervisor Prof. Simon Bennett, without your expertise and advice, both scientific and technical, this body of work would not have been possible. Your help in developing my technical skills has been invaluable. To my third supervisor, Dr. Joe Causer, I am very grateful for your support and guidance in making the decision to pursue my PhD. I would also like to thank Prof. Digby Elliott and Dr. Geoff Bird for their comments and guidance on numerous drafts and helping to advance my statistical analyses. Thank you also to everyone at Autism Together for their assistance, especially those at Step into Work who participated in my studies. Additionally, I would like to thank my fellow PhD students, past and present, for helping to maintain my sanity and I would like to thank Dr. Matthew Andrew especially for his help in my first year. To my parents, Mark and Elaine, you made sure there was a roof over my head and supported me financially through all of this. I may never be able to truly repay you, but I will do my best. To Lauren, you've endured all the ups and downs along the way, and have stuck with (tolerated) me regardless, thank you. Finally, to all my family, friends, and volunteers, I thank you.

II Table Legends

III Figure Legends

IV Abbreviations

Abbreviation	Long Form
ASD	Autism Spectrum Disorders
ADOS	Autism Diagnostic Observation Schedule
AON	Action Observation Network
APA	American Psychiatric Association
CDC	Centre for Disease Control and Prevention
CE	Temporal constant error
CNS	Central Nervous System
CRT	Cathode Ray Tube
DSM	Diagnostic and Statistical Manual of Mental Disorders
EEG	Electroencephalography
fMRI	Functional Magnetic Resonance Imaging
GOADI	Goal-Directed Imitation
IFG	Inferior Frontal Gyrus
ILp	Imitation Learning Protocol
IPL	Inferior Parietal Lobule
MEG	Magnetoencephalography
MNS	Mirror Neuron System
mPFC	Medial Prefrontal Cortex
OPp	Observational Practice Protocol
PMC	Premotor Cortex
RMSE	Root Mean Square Error
S-R	Stimulus-Response
SD	Standard Deviation
sdPA	Spatial Variability at Peak Acceleration
sdPV	Spatial Variability at Peak Velocity
SRS	Social Responsiveness Scale
STORM	Social Top-Down Response Modulation
STS	Superior Temporal Sulcus
TMS	Transcranial Magnetic Stimulation
tPHV	Percentage-Time-to-Peak-Hand-Velocity
TPJ	Temporo-Parietal Junction
tPSEV	Percentage-Time-to-Peak-Smooth-Eye-Velocity
VE	Temporal variable error
VSTT	Visuomotor Sequence Timing Task
WASI	Wechsler Abbreviated Scale of Intelligence

V Publications and Presentations

Foster, N. C., Bennett, S. J., Causer, J., Bird, G., Andrew, M., & Hayes, S. J. (2018). Atypical biological kinematics are represented during observational practice. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(6), 842.

Foster, N. C., Bennett, S. J., Causer, J., Elliott, D., Andrew, M., & Hayes, S. J. (2016). Sensorimotor adaptation underpins imitation learning of biological motion kinematics in autism spectrum disorders. Paper presented at the 2016 International Meeting for Autism Research, Baltimore, United States of America. Abstract retrieved from http://www.autism-insar.org

VI Thesis Abstract

The aim of the current thesis was to examine the role of sensorimotor integration during sensorimotor learning and control processes in autism spectrum disorders. Autistic participants were matched (IQ, age, gender) with control participants across three experimental chapters (chapters three-five) within the contexts of motor learning, imitation and observational practice. An additional control experiment (chapter two), which examined observational practice, was also completed in order to determine suitable data collection and analysis techniques. In *Chapter Two* it was confirmed that atypical biological kinematics properties are coded during observational practice via underlying sensorimotor processes, rather than spatial encoding of peak velocity via processes associated with stimulus-response compatibility. In *Chapter Three* it was observed that autistic participants can successfully form new internal action models, but their movements are characterised by increased variability in the spatial position of peak acceleration. In *Chapter Four*, it was shown that autism participants were able improve their imitation of atypical biological kinematics when presented in a fixed trial-order. Suggesting that in part imitation difficulties in autism may be related to differences in sensorimotor processing and integration. In *Chapter Five* it was observed that individuals with autism, like typically developed controls, can code atypical biological kinematics via observational practice. There are however potential differences in the processing of reafference when updating an existing internal action model. The findings of the current thesis will be summarised and critically evaluated with regards to the current literature. Theoretical implications will be considered, and potential future directions and research applications will be discussed.

1 Chapter One: Introduction

1.1 Prologue

The current thesis contains three independent experimental chapters (chapters three - five) examining the role of sensorimotor integration in autism spectrum disorder (henceforth autism) across the modalities of motor learning, imitation, and observational practice. Prior to these, an initial experiment (chapter two) investigating observational practice in control participants was conducted in order to determine suitable data collection and analysis techniques. This introduction will therefore provide a review of the key existing literature that underpins the motivation for the experimental chapters and in doing so will develop the rationale for the experimental manipulations. This review will be presented within five thematic sections: (1) autism; (2) sensorimotor integration and control; (3) motor learning; (4) sensorimotor processing; (5) imitation. It should be noted that this introduction is not intended to provide an exhaustive review of all current the literature within these themes, but instead to provide a synthesis related to the key research question underpinning the experimental chapters.

1.2 Autism Spectrum Disorder

Autism is a neurodevelopmental disorder associated with core difficulties in social communication, as well as restricted and repetitive behaviours and interests (American Psychiatric Association, 2013). Autism was first documented by Leo Kanner (1943), who provided a detailed case study of eleven children with, what he termed, an ‘autistic disturbance of affective contact’. In this seminal paper he described that the children showed limited communicative language and a reduced interest in social contact, alongside restricted and repetitive behaviours. Hans Asperger (1944) also published a description of autism in the following year, namely ‘Autistic psychopathy in children’. Similar to Kanner (1943), this paper described

children who showed difficulties in social interaction, including both verbal and non-verbal communication, as well as specific and limited interests. It is interesting to note that these observations (Asperger, 1944; Kanner, 1943) are still encompassed in the primary features of autism (Harris, 2018), although autism is accepted as being high in heterogeneity (Frith & Happé, 2005; Kanner, 1971).

Diagnosis

Initially, many considered the condition described by Kanner (1943) to be an early manifestation of schizophrenia until the distinction between the two was clarified in 1971 (Kolvin, 1971). This led to the Diagnostic and Statistical Manual of Mental Disorders (DSM-III; American Psychiatric Association, 1980) and the classification ‘early infantile autism' that, distinct from schizophrenia, was categorised by differences in language development and unusual responses to others and the environment, with an onset before 30 months. The term ‘Asperger syndrome’, having been proposed to describe Hans Asperger’s (1944) observations (Wing, 1981), was then introduced as a diagnostic term by DSM-IV (American Psychiatric Association, 1994) alongside 'autistic disorder'. This new term was used to describe higher functioning individuals whose IQ and verbal communication skills were in the normal range, but showed differences in non-verbal communication as well as limited interests (Asperger, 1944). However, with the introduction of DSM-5 (American Psychiatric Association, 2013), the previous terminology was phased out and encompassed within the term 'autism spectrum disorder'. Here, two key diagnostic criteria are used; (1) differences in social communication and (2) restricted and repetitive behaviours and interests. Notably, both of these are close to Kanner’s (1943) original criteria of 'autistic aloneness' and 'preservation of sameness' (Harris, 2018).

Prevalence

The aforementioned changes in diagnostic criteria have, in part, been suggested to underpin the reported increases in the prevalence of autism (Weintraub, 2011), whereby prevalence is an estimate of the number of known cases within a period of time. Early estimations for the prevalence of autism were 4 cases per 10,000 (Rutter, 1978), suggesting it to be relatively uncommon. More recent estimates provided by the Centre for Disease Control and Prevention (CDC), suggest that in the USA, the prevalence of autism has increased by an approximate 150% from the year 2000 (6.7 per 10,000 children) to 2014 (16.8 cases per 10,000 (16.8 cases per 10,000; Baio et al., 2018). The UK observed a similar significant increase in prevalence during the preceding decade, from 4 per 10,000 children born in 1988 to 25 per 10,000 children born in 1997. This has since plateaued in the UK (Hagberg & Jick, 2010), with no significant changes in these estimates between 2004 and 2010 (Taylor, Jick, & MacLaughlin, 2013). Through this period, estimates have remained at approximately 38 per 10,000 in boys, aged 8, and 8 per 10,000 in girls, suggesting that autism is more common among males (Taylor et al., 2013). It is also noteworthy that high familial risk has been highlighted in autism (Ozonoff et al., 2011), whereby the siblings of an autistic individual are more likely to have autism, resulting in the suggestion that the aetiology of autism potentially has a genetic component (Losh, Sullivan, Trembath, & Piven, 2008).

Characteristics of Autism

Social Interaction

One area that is often used to characterise autism is difficulties in social interaction. Social differences are one of the characteristics that distinguish autism from other developmental disorders, such as Rett syndrome (Harris, 2018). Moreover, it is important to note difficulties with social interaction can impact autistic individuals regardless of their cognitive or language ability (Carter, Davis, Klin, & Volkmar, 2005). Examples include social-orienting (Dawson, Meltzoff, Osterling, Rinaldi, & Brown, 1998), whereby autistic individuals fail to orient their attention to social stimuli (e.g., someone waving) in their environment, as well as reduced eye contact (e.g., attending to another's eyes during conversation) (Senju & Johnson, 2009). Lack of social eye contact is currently used during diagnostic assessments for autism (Lord et al., 2012), and can be observed from as early nine months of age (Baranek, 1999). Similarly, infants who would later be diagnosed with autism, could be differentiated from those with other developmental conditions and typically developing infants by a delayed response to verbal cues (i.e., their name) and an aversion to social touch (Baranek, 1999). These difficulties can also have wider impacts on autistic individuals (White, Keonig, & Scahill, 2007) such as employment (Hendricks, 2010), and greater loneliness (Bauminger & Kasari, 2000).

Communication

Understanding the development of language and communication can be pivotal in autism, with differences between the fluency and flexibility of language being used to determine autism severity as well to differentiate from other developmental disorders (Tager-Flusberg, Paul, & Lord, 2005). Autistic children at the age of two have been shown to exhibit the expressive and receptive language

abilities of those expected of a nine month old typically developing child (Lord, Pickles, Dilavore, & Shulman, 1996). Moreover, communication development in autism is suggested to be regressive (Lord, Shulman, & DiLavore, 2004), as it was observed that some children who had developed some use of meaningful language experienced word loss alongside other social changes at approximately two years of age. Lord and colleagues (2004) described this phenomenon as unique to autism, but not universal, and when observed could be used as a signpost for a potential future diagnosis. Differences in communication skills in autism are not exclusive to language development. Differences in the use of non-verbal communication have also been observed, with children at risk of autism being shown to produce significantly fewer gestures at both twelve and eighteen months, alongside reduced language comprehension (Mitchell et al., 2006).

Restricted and Repetitive Behaviours

Examples of restricted and repetitive behaviours are: stereotyped (e.g., hand-flapping), ritualistic (e.g., a set routine), self-injurious (e.g., head-banging), compulsive (e.g., hoarding), and restricted interests (e.g., a preoccupation with a given subject) (Lam & Aman, 2007). No single explanation or cause of these behaviours in autism has yet been identified (Turner, 1999), but several explanations have been proposed. It has been suggested that restricted and repetitive behaviours are learned and then maintained by reinforcement provided by their sensory consequences (Lovaas, Newsom, & Hickman, 1987). A second explanation is that they are a consequence of weak central coherence (Frith & Happé, 1994), whereby autism is associated with a preferential processing of local, rather than global environmental features. This could then result in an autistic individual not paying attention to a wider context and focussing on a small detail or preoccupation. It has

also been proposed that these behaviours could be then related to an executive function issue in autism (Lopez, Lincoln, Ozonoff, & Lai, 2005). It must however be noted that these potential explanations are not necessarily mutually exclusive, and the restricted and repetitive behaviours often observed in autism may be the result of a combination of factors (Turner, 1999).

Mentalising

Differences in the ability to infer the mental states of others, known as mentalising, have commonly been described in autism (for a review see Chung, Barch, & Strube, 2013). The ability to make these inferences regarding the desires, beliefs and/or emotions of others (Premack & Woodruff, 1978) formed the basis of an early account for the aforementioned difficulties in social interaction and communication, that is the 'theory of mind' hypothesis (Baron-Cohen, Leslie, & Frith, 1985; Baron-Cohen, 1989). For example, Baron-Cohen and colleagues (1985) found only 20% of autistic participants were able to successfully pass the 'Sally-Anne' false-belief test, compared to 85% of control participants and 86% of participants with Down Syndrome. This test consists of a story about two dolls, Sally who has a basket and Anne who has a box. Participants are told that Sally puts a marble in her basket and then leaves the room. Once Sally has left, Anne removes the marble from the basket and places it in her box. Sally then returns and looks for the marble. Participants are then asked to report where Sally will look her for marble. The correct response being that she will look in her basket, not the location of the marble in the new box, as the test is assessing the participants' ability to consider Sally's false belief.

It has been proposed that a key contributing factor towards behavioural symptoms in autism may be altered cognitive processes (Happé, Ronald, & Plomin,

2006). Jones et al. (2018) aimed to model how parent-reported measures of social communication and restricted repetitive behaviours are associated with cognition. They examined both theory of mind and executive function in a sample of 100 autistic adolescents and found that theory of mind ability was significantly associated with both social communication symptoms and restricted repetitive behaviours. In contrast, executive function was only related to participants' theory of mind ability, suggesting that theory of mind may account for autistic symptoms (Jones et al., 2018). Other experimental work has examined how theory of mind relates to behaviour in autism. For example it has been suggested that theory of mind relates to autistic participants ability to inhibit imitation (Spengler, Bird, & Brass, 2010). The ability to inhibit imitation was shown to be related to both behavioural and neuroimaging measures of theory of mind, suggesting that imitation and mentalising share common processing which likely occurs in the medial prefrontal cortex (mPFC) and the temporoparietal junction (TPJ) (Spengler et al., 2010). Theory of mind is also suggested to be related to language development such that autistic children rely on verbal mediation to pass false-belief tasks, whereas typically developing children will utilise cognitive mechanisms that are not related to language (Tager-Flusberg, 2000). For example, Happé (1995) found that typically developing children had a fifty percent chance of passing false belief tasks with a verbal age of four years old, whereas for autistic children a verbal age of over nine was needed to have the same chance.

It must however be noted that the theory of mind hypothesis has not gone unchallenged (Boucher, 2012; Scheeren, de Rosnay, Koot, & Begeer, 2013). Data from tasks that used stories to examine second-order false belief, emotional display rule understanding, double bluff, and faux pas showed no group differences for any of the aforementioned advanced theory of mind skills (Scheeren et al., 2013). That

said, this evidence for typical mentalising abilities in autism is based on a group of high-functioning autistic adults, rather than autistic children like in the Sally-Anne task (Baron-Cohen et al., 1985; Baron-Cohen, 1989) Indeed, Scheeren et al. (2013) also observed a positive correlation between theory of mind ability and age, although it must be noted that they did highlight the possibility that their findings may be a function of verbal ability, due to the nature of their task, rather than mental state reasoning. Moreover, it has previously been shown that autistic participants who show similar theory of mind abilities to controls in lab-based measures remain less able than controls in everyday social settings (Peterson, Garnett, Kelly, & Attwood, 2009). In typically developed groups these abilities are formed via their social experiences (Carpendale & Lewis, 2004), and as such solving these lab-based tasks may be driven by general logic to understand mental states (Scheeren et al., 2013), rather than experience-dependent social skills.

Motor Behaviour

Investigations into differences in the motor system in autism (Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Gowen & Hamilton, 2013; Leary & Hill, 1996) have also increased in prominence. This is in part due to reports that compared to neurotypical controls, autistic individuals are: i) generally clumsier and less coordinated than controls (Ghaziuddin & Butler, 1998); ii) less able to execute skilled gestures to command (praxis); iii) different in their acquisition of new sensorimotor skills (e.g., language; throwing a ball) important for interacting within their environment; and iv) impaired in the development of new actions via imitation learning (Mostofsky et al., 2006). Indeed, delays in motor development in autism have been evidenced during infancy (for a review see Bhat, Landa, & Galloway,

2011), with motor ability being shown to correlate with speech fluency (Gernsbacher, Sauer, Geye, Schweigert, & Hill Goldsmith, 2008).

Importantly, it has often been proposed that motor differences may contribute to the social difficulties experienced by autistic individuals (J. Cook, 2016; J. Cook, Blakemore, & Press, 2013; Haswell, Izawa, Dowell, Mostofsky, & Shadmehr, 2009; Mostofsky & Ewen, 2011). The premise is that if motor experience facilitates action perception (Casile & Giese, 2006), the altered motor experience of an autistic individual may impact the ability to recognise and understand the actions of others, and vice versa (J. Cook, 2016). For example, it has been shown that autistic participants have difficulties recognising emotions from the facial expression of typically developing models (Lindner & Rosén, 2006), as well as controls having the same difficulties with autistic facial expressions (Brewer et al., 2016). The following paragraphs will consider in more detail the evidence for motor differences between autistic and neurotypical controls during whole-body coordination (i.e., locomotion) and upper-limb coordination (e.g., reaching, aiming) tasks.

One specific area of motor behaviour that has been shown to differ in autism is locomotion (Calhoun, Longworth, & Chester, 2011; Rinehart, Tonge, et al., 2006; Vernazza-Martin et al., 2005). Vernazza-Martin and colleagues (2005) investigated gait and balance control during walking in autistic children. Although their analysis of gait found that both autistic and control children walked similarly with no significant differences in stride duration, gait velocity, cadence or the time spent in the swing or stances phases of stride, there was a difference in step length. Autistic children were shown to take significantly shorter steps than their control counterparts. Furthermore, the same study also showed increased variability in the position of the head, shoulders and trunk during walking in the autism group. In a similar study of gait in autism, Rinehart, Tonge, et al. (2006) provided comparisons

within the autism spectrum (i.e., Autism and Asperger's; DSM-IV-TR). Like Vernazza-Martin et al. (2005), they found differences in the step length, with those with an autism diagnosis showing greater variability than both control and Asperger's participants. These findings show that not only are there potential motor differences in autism when compared to controls, but there is also heterogeneity within the autistic phenotype.

Of particular relevance to the current thesis is that differences in motor behaviour have been observed in autism during upper limb movements. For example, when performing manual aiming movements, autistic participants tend to exhibit a greater total duration (i.e., movement time) than control participants for the same amplitude (Glazebrook, Elliott, & Lyons, 2006). Similar differences have also been shown in autism when executing a three-segment motor sequence (Hayes et al., 2018). Although Hayes and colleagues (2018) provided knowledge of results related to how fast or slow participants were compared to the criterion movement time (1700 ms) as feedback following every trial, autistic participants performed movements that were on average 362 ms slower than the control participants. Given these timing differences, it may not be surprising that there have been several studies on movement kinematics in autistic individuals (J. Cook et al., 2013; Glazebrook et al., 2006). When asked to perform a horizontal sinusoidal arm movements, Cook and colleagues (2013) observed that autistic individuals produced movement that had more jerk, alongside greater magnitudes of peak velocity and peak acceleration. These differences were shown to correlate with participants' autism severity, suggesting that kinematic differences may be a potential indicator of the autism phenotype. Similarly, Edey et al. (2016) showed increased jerk when autistic participants performed a more complex object-based task that involved creating animations using cardboard triangles via magnets. Together, these findings indicate

that kinematic differences during motor behaviour are present during both simple and complex motor tasks.

1.3 Sensorimotor integration and control

Differences in motor behaviour of autistic individuals described could be attributed to numerous factors, possibilities of which include differences in muscle tone (Maurer & Damasio, 1982) and altered functioning of the central nervous system (CNS) (J. Cook et al., 2013). With regards to the latter, there has been a growing interest in the role that sensorimotor integration has on motor behaviour in autism. Sensorimotor integration is the capacity of the CNS to process and integrate sensory information from multiple sources (i.e., vision, proprioception), whilst simultaneously transforming this information into a motor output (Machado et al., 2010). The neural basis of this processing is proposed to occur across a three level hierarchy: medullar, sub-cortical and cortical (Bizzi, Tresch, Saltiel, & d'Avella, 2000). At the medullar level, afferent information from the skin, muscles and joints is processed in order to perform reflex actions. At the sub-cortical level, sensory information from areas such as the vestibular system is used in the production of the spinal cords motor repertoire to execute more complex reactions. An example of which could be postural adjustments to movement disturbances caused by an individual's own actions (Wolpert & Flanagan, 2001). Problems at this level of sensorimotor integration could perhaps offer some explanation of the greater variability in balance control during locomotion in autism that was previously described (Vernazza-Martin et al., 2005). Finally, there is the cortical level is where sensory information is processed in what are termed the association areas of the brain (i.e., pre-frontal cortex, parietal cortex) in order to process sensory information

from our environment and produce a motor output at the limb (Monfils, Plautz, & Kleim, 2005).

In order to better understand the role of sensorimotor integration at the cortical level and its potential influence on motor behaviour, and thereby social interaction in autism, it is instructive to consider a model (see figure 1.1; adapted from Gowen & Hamilton, 2013) of the underlying sensorimotor control processes (Blakemore, Frith, & Wolpert, 1999; Elliott et al., 2010; Gowen & Hamilton, 2013; Shadmehr & Krakauer, 2008; Wolpert & Ghahramani, 2000). In the case of an

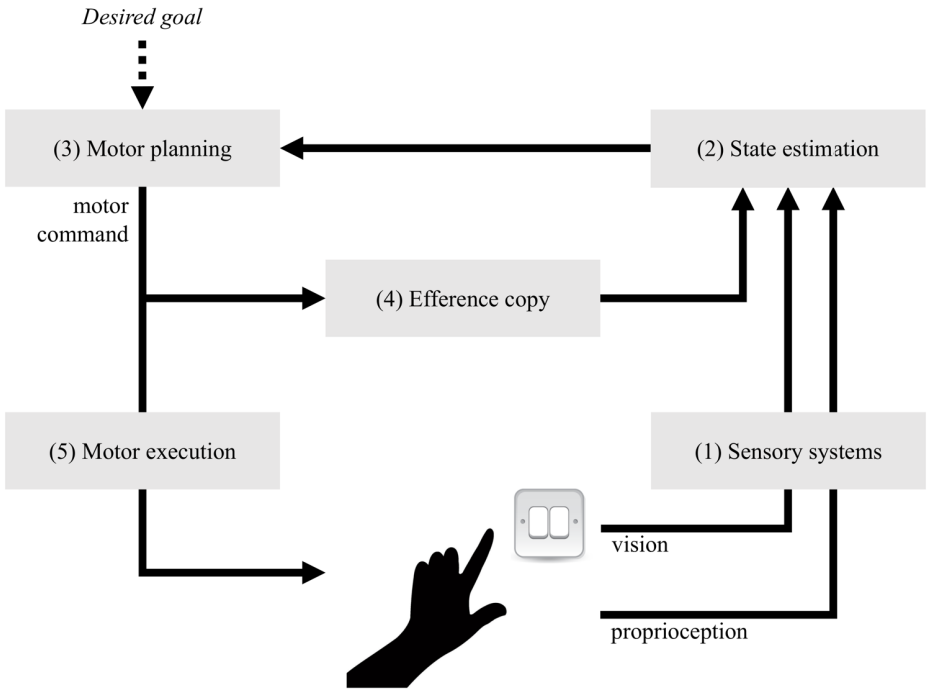

Figure 1.1: Overview of sensorimotor integration and motor control processes involved during motor execution (adapted from Gowen & Hamilton, 2013).

everyday task, such as turning on a light switch, an individual must first use their visual and proprioceptive systems (1) to extract task-relevant information. This could include the current position of their hand, the position of the light switch, and the distance these are apart. This information is then used to establish the participant's current state (2) relevant to the desired goal of the action (i.e., pressing the switch). The resulting information is the compared with the individual's pre-existing motor

repertoire in order to formulate a plan (3) that will allow them to solve the problem (i.e., press the light switch). This plan is then used to generate a motor command that specifies the muscular forces to be produced at the limbs. The motor command is used in two separate but related processes, namely to form part of an efference copy (4), as well as to execute the desired action at the limb. As the movement progresses, this cycle repeats with the individual being able to modify their motor output online to generate new motor commands that correct for any errors and ensure the limb reaches the target.

More specific details on how the sensorimotor control processes outlined in the above model operate when controlling manual aiming movements have been proposed by Elliott and colleagues in their multiple process model of limb control (see Figure 1.2; Elliott et al., 2010). In line with Woodworth's (1899) two-component model, Elliott and colleagues suggest that goal-directed aiming movements consist of two distinguishable phases: a primary movement phase such as reaching for a light switch; and a corrective phase that reduces any discrepancy between the limb position and the light switch. Key to control of these phases, and thereby accurate and precise motor execution, is the role of online motor control. This occurs, sequentially, as follows: (1) early efferent control involving the comparison of expected efference to the actual efference; (2) continual afferent control based on the comparison of visual and proprioceptive feedback from the limb to the expected sensory consequences; and (3) late visual control related to the limb and the target position. Key to the operation of these processes is sensorimotor integration, which occurs continually throughout a movement, thereby enabling an individual to update their state estimate and modulate their motor output accordingly

(Figure 1.1; Blakemore et al., 1999; Elliott et al., 2010; Shadmehr & Krakauer, 2008; Wolpert & Ghahramani, 2000).

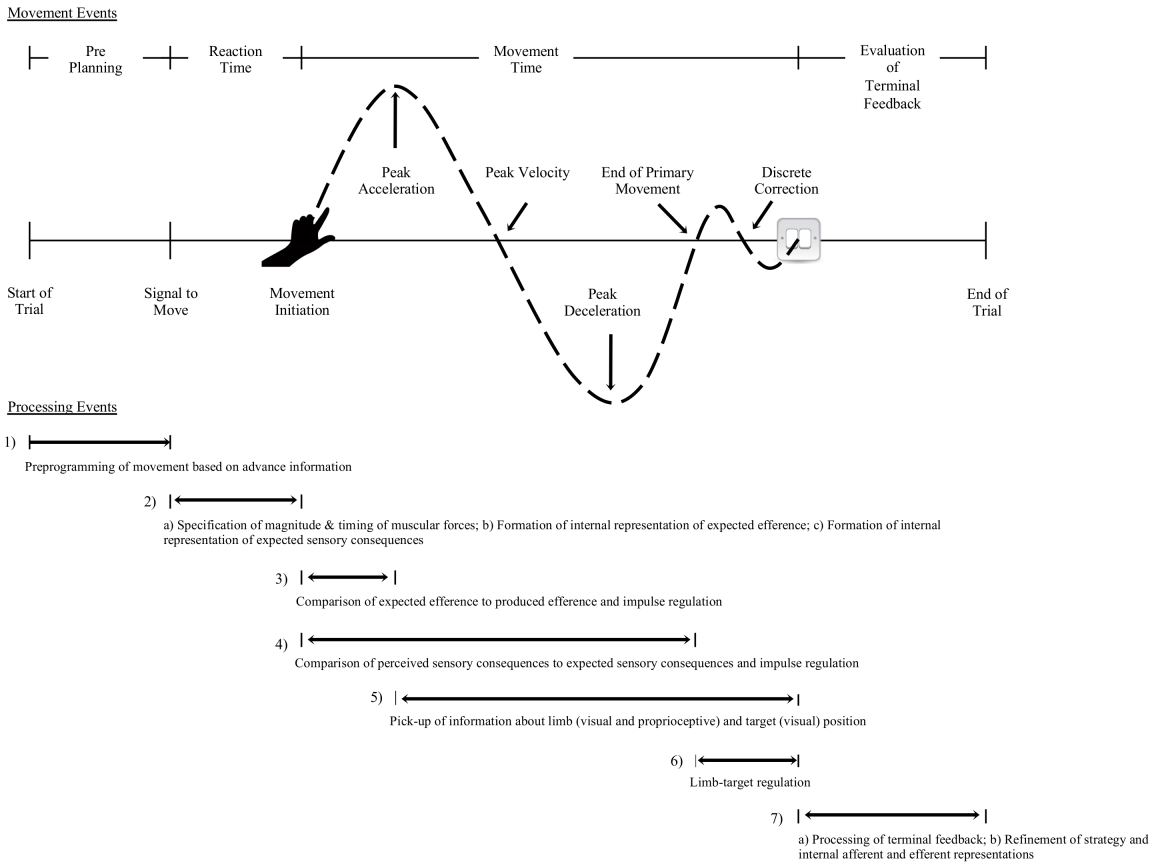

Figure 1.2: Schematic representation of the multiple-process model of control for goal-directed movements (adapted from Elliott et al., 2010).

In the following subsections, the underlying sensorimotor control processes (sensory systems; state estimation; motor planning; feedforward motor control) that contribute to both motor and social skills (Blakemore et al., 1999; Elliott et al., 2010; Gowen & Hamilton, 2013; Shadmehr & Krakauer, 2008; Wolpert & Ghahramani, 2000) will be considered with particular reference to autistic individuals. Consistent with *Figure 1.1 (adapted from* Gowen and Hamilton (2013)), these subsections will be considered sequentially. However, it is not the intention to suggest that these underlying sensorimotor control processes are independent from one another. As

stated, in order to execute a desired action an individual must continually process and integrate sensory information from multiple sources (i.e., vision, proprioception (Machado et al., 2010). This sensorimotor integration then not only facilitates the production of a global movement, but also the production of graded adjustments throughout (Elliott et al., 2010).

(1) Sensory systems

Using the adult/adolescent sensory profile (Brown & Dunn, 2002), a self-report questionnaire that assesses sensory processing across modalities (e.g., taste/smell, movement, visual, touch, activity and auditory), it has been shown that altered sensory processing is prevalent in autistic adults when compared to matched controls (Crane, Goddard, & Pring, 2009). Indeed, it has been suggested that autistic individuals show a preference for processing local detail, over global contextual information which, as stated previously, has been referred to as weak central coherence (Frith & Happé, 1994; Happé & Frith, 2006). Linked to this are reported differences in visual search in autism (O'Riordan & Plaisted, 2001; Plaisted, O'Riordan, & Baron-Cohen, 1998). Plaisted et al. (1998) found that although autistic participants were more accurate than controls in discriminating novel stimuli, they were less accurate when familiar stimuli, to which they had been pre-exposed, were used. One suggestion for their poor performance with familiar stimuli could be that they have problems in shifting attention (Courchesne et al., 1994). That is, it is possible that autistic participants only focussed their attention towards one localised area during pre-exposure, attending to a local detail of a stimulus rather than the whole of it (i.e., weak central coherence). In this study the stimuli from the pre-exposure and test conditions shared common features to facilitate discrimination learning. However if these areas were not attended to by the autistic participants this

learning effect would have been obstructed, meaning issues in shifting attention would negatively impact the autistic participants discrimination ability for the familiar stimuli (Plaisted et al., 1998).

Sensory difficulties have also been associated with differences in the processing of faces (Klin et al., 1999), as well as biological motion (J. Cook et al., 2013; J. Cook, Saygin, Swain, & Blakemore, 2009). Cook and colleagues (2009) examined the psychophysical thresholds for biological motion detection in autistic and control participants by showing animations that morphed biological motion with constant velocity. In this study, threshold refers to the proportion of constant velocity required, within the animation, for the participant to no longer be able to discriminate the animation as less natural than a reference. Therefore, the lower the threshold the more sensitive a participant is to perturbations of biological motion. They found that the threshold in control participants was 30%, compared to 40% for the autistic participants. This reduced sensitivity in autism has been suggested to be a developmental consequence of autistic children spending less time attending to biological motion (Klin, Lin, Gorrindo, Ramsay, & Jones, 2009), but has also been shown to be potentially associated with motor differences (J. Cook et al., 2013).

How sensory systems are recruited and facilitate sensorimotor integration during motor execution has also been examined in autism. For example, Glazebrook, Gonzalez, Hansen, and Elliott (2009) examined the use of visual feedback to establish the specificity of the underlying sensorimotor control processes in autism. The results showed that both autistic and control groups took longer to execute movements when vision was available, but this increase was significantly greater in the autism group than the control group. This suggests that both groups successfully recruited the visual and proprioceptive systems, but potential processing differences may result in the autism group not being able to integrate these two modalities as

efficiently. Further evidence for the altered integration of vision and proprioceptive sensory information in autism has been shown during motor learning (Haswell et al., 2009). Here, participants practised a movement where they moved a manipulandum within a specified task protocol. Following practice, they completed a test-phase where on error-clamp trials this task was generalised to a different workspace where the limb was rotated by 45 degrees. Here they completed the same task but moved either to target directly in front of them, therefore having the same visual relationship as in practice, or where the target was rotated by 45 degrees, meaning it had the same proprioceptive relationship to the participants. Haswell and colleagues (2009) found that although control and autistic participants produced similar force characteristics in the practice condition, autistic participants were less able to generalise what they had learned to the new visual condition. The suggestion is that proprioceptive sensory information was more effectively processed than visual information during motor learning in autism. Overall, then, the evidence described above from perception tasks (Klin et al., 1999), as well as during motor execution (Glazebrook et al., 2009) and learning (Haswell et al., 2009), points to altered integration and processing of visual information in autism compared to neurotypical controls.

(2) State estimation

Prior to forming an effective motor plan, an individual must first create an accurate representation of their environment and importantly, their position relative to the target they intend to move to. In the example of reaching to press a light switch, information is needed regarding the size and position of the target, the position of the hand and the distance between them. This requires multisensory information processing (Gowen & Hamilton, 2013; Molinari, Restuccia, & Leggio,

2009), which enables the integration of the different sensory signals (i.e., vision, proprioception), alongside pre-existing models from the individuals motor repertoire to form an accurate state estimate. This state estimate can then be used to create a motor plan that either: (1) provide the motor system with the required information to make online motor adjustments, or (2) identify sensorimotor patterns that fit with pre-existing models from the individuals motor repertoire (Molinari et al., 2009).

During this multisensory information processing, it is important to only extract and integrate task relevant information, filtering out any additional environmental noise. One means of doing so is via spatial and temporal windows, whereby only sensory information that occurs close in space or time is processed (Spence, Pavani, Maravita, & Holmes, 2004). With regards to autism, most research has focussed of the integration of auditory and visual information due to its links with social communication (Baum, Stevenson, & Wallace, 2015). Here it has been suggested that the temporal window in which these sensory modalities are integrated is longer in autism than in controls (Foss-Feig et al., 2010; Kwakye, Foss-Feig, Cascio, Stone, & Wallace, 2011). For example, Foss-Feig and colleagues (2010) used a flash-beep illusion in which the presentation of multiple auditory tones (beeps) alongside a singular visual stimulus (flash) often results in the false perception of multiple flashes. By varying the latency between the presentations of the stimuli, Foss-Feig et al. could examine the extent of the temporal window that would produce this false perception. They found that this window was approximately 300 ms in control participants compared to approximately 600 ms in the autistic group. If applied to the motor task of reaching for a light switch, the implication is that altered multisensory information processing issues could result in a larger temporal window being required to integrate visual and proprioceptive information effectively to form an accurate state estimate. If this results in any

discrepancies in the state estimate, there could be a knock-on effect on movement time and/or variability in the subsequent action.

Another protocol used to examine multisensory information processing in autism is the rubber hand illusion (Cascio, Foss-Feig, Burnette, Heacock, & Cosby, 2012). This consists of participant observing a rubber hand on a table being stroked whilst their own hand, which is underneath the table out of sight, is also stroked. Here a sense of ownership is transferred to the rubber hand as a proprioceptive drift occurs with participants incorrectly reporting their own hand to be closer to the rubber hand. Although Cascio et al. (2012) did show evidence of this phenomena occurring in autism, they reported that time taken for this proprioceptive drift to occur was much greater than in controls. This is consistent with the suggestion that multisensory information processing is functional but takes longer in autism.

An alternative way to examine state estimation is via the reprogramming of a pre-planned movement (Nazarali, Glazebrook, & Elliott, 2009). In order to perform motor tasks and interact with others we need to extract the required task relevant information from what can be an ever-changing environment. Therefore, how effectively an individual can identify changes to their environment and form a new state estimate of their location and the position of target can be examined by manipulating task constraints after a movement has already been prepared (Nazarali et al., 2009). For example, after participants had prepared a manual aiming movement, the task was manipulated so that on 20% of trials there was an alteration or either the target goal position, or the hand to be used. Although both groups showed increases in reaction time as a function of having to form a new state estimate in order to reprogram a movement, this difference was greater for the autism group. This finding suggests that the ability to extract task relevant

information and estimate the current state may be altered in autism, potentially due to the aforementioned issues in multisensory information processing.

(3) Motor planning

In order to generate a series of motor commands that underpin the achievement of a goal-directed movement, an individual must combine information regarding their current state with their desired goal (Gowen & Hamilton, 2013). For example, in relation to turning on a light switch, they must generate a motor command to move the limb the required distance, as well as another to then produce enough force to successfully depress the switch (Rosenbaum & Jorgensen, 1992). A common way to evaluate motor planning is through the measurement of reaction times. It is during this period where an individual specifies the magnitude and timing of the muscular forces required, as well as forming internal representations of the to-be-executed movement for online control (Elliott et al., 2010). In general, those with autism have been shown to demonstrate longer reaction times than controls (Glazebrook et al., 2006; Glazebrook, Elliott, & Szatmari, 2008; Glazebrook et al., 2009; Nazarali et al., 2009; Rinehart, Bradshaw, Brereton, & Tonge, 2001). For example, Rinehart et al. (2001) used a motor reprogramming protocol where participants performed reciprocating movements between two targets. During a trial, one of two additional targets would be illuminated signalling that participants had to press a button they were not expecting to press. This was termed an 'oddball' trial and participants were informed there would only be one per trial. This should therefore have resulted in faster reaction times for the movement immediately following the 'oddball' as participants would have advance knowledge of where they would be moving to. The authors found that autistic participants did not show this advantage, with some actually exhibiting slower reaction times, suggesting that the

autistic participants may not utilise advance information effectively during motor planning.

These findings supported previous work (Hughes, 1996), that had showed autistic individuals exhibit planning differences in goal-directed sequences. Specifically, autistic individuals were found to adopt a comfortable hand position when grasping a rod, rather than using a hand-position that although less comfortable when grasping, would result in a comfortable position when placing the rod in a target. In contrast, control participants showed a preference for planning their movements to finish in position of end-state comfort (Cohen & Rosenbaum, 2004; Rosenbaum & Jorgensen, 1992; Rosenbaum et al., 1990). This finding supports the hypothesis that motor planning is altered in autism, with participants choosing not to alter their actions (i.e., grip selection) relative to the task constraints (i.e., rod position in relation to target). Conversely, later research investigating grip selection tasks in autism (Hamilton, Brindley, & Frith, 2007; van Swieten et al., 2010) has reported findings that differ to this previous work, positing that autistic and control participants show similar behaviour in relation to end-state comfort. For example, van Swieten et al. (2010) found that children with and without autism, between nine and fourteen years of age, both showed a bias towards end-state comfort in a grip selection task. However, this bias was less common younger children (5 – 8 years), regardless of diagnosis, suggesting that difficulties in this type of grip selection task may be associated with age and motor development, rather than any motor planning issues in autism.

Grip selection is not the only way to examine motor planning across sequential movements. A useful alternative is to study how movement times are affected by task constraints (Fabbri-Destro, Cattaneo, Boria, & Rizzolatti, 2009). Fabbri-Destro et al. (2009) asked both an autistic and a control group to perform two

action sequences where after completing a reach to an object, that object was placed in either a small or a large container. It was expected that the first movement (i.e., the reach) would be modulated by the task difficulty (i.e., the size of the container), with movement duration increasing for the more difficult task (i.e., small container). Although both groups showed significant increases in movement time for the place action when using the small container, a group difference was present in the first movement. Specifically, only the control group showed an additional increase in movement time for the reach component in the more difficult task using the small container. This suggests that whilst the control group were able to plan both actions within the sequence prior to execution, the autism group planned each action independently. These findings therefore provide further evidence that differences in motor planning are present in autistic participants.

(4) Feedforward motor control

As previously stated, when reaching for a light switch an individual will form a state estimate and generate a motor plan in order to effectively drive the limb towards their goal (i.e., the light switch). Based on these information sources, an individual produces a forward model which can be used to control their movement and predict the expected outcomes before afferent information has been processed (Ghez, Hening, & Gordon, 1991; Miall & Wolpert, 1996; Wolpert & Flanagan, 2001; Wolpert & Kawato, 1998). The ability of humans to use these forward models to predict changes in state have been shown by examining how external stimuli are perceived in comparison to self-produced stimuli (Blakemore et al., 1999). For example, in the study by Blakemore et al. (1999) a robot arm was used to stroke the palm of a participants right hand in the externally produced condition, whereas in the self-produced condition the stroking movement was produced by the participants

moving a connected robot with their left hand. In this control experiment, it was found that participants rated the tactile sensation of a self-produced stimulus to be less intense than that of a similar stimulus that was produced externally. However, if either the self-produced stimuli's trajectory or timing was perturbed, participants' ratings of tactile sensation increased. This finding demonstrates that a forward model is less effective when there is a discrepancy between what an individual predicts to be the consequences of an action and its actual consequences (Blakemore et al., 1999). The same effects, and thus functioning of a forward model, has been shown in autism, with autistic participants reporting tactile sensation to be less intense or self-produced stimuli compared to externally produced stimuli (Blakemore et al., 2006)

That said, differences in feedforward control related to prediction have been shown in grip force tasks (David et al., 2009; David, Baranek, Wiesen, Miao, & Thorpe, 2012; Mosconi et al., 2015; Wang et al., 2015), as well as manual loading (Schmitz, Martineau, Barthélémy, & Assaiante, 2003). Mosconi et al. (2015) found that autistic participants produced less accurate initial force contractions, resulting in greater peak rate of force production and overshooting. These findings suggest that these issues may arise from difficulties in the planning component of feedforward control in relation to the specification of the required muscular forces to produce the desired action (Elliott et al., 2010). Moreover, Mosconi and colleagues highlight that these differences were only found for low-force contractions, and not during larger force contractions. A reason for this is that larger force contractions are typically associated with greater movement durations which therefore provide enough time for individuals to process visual sensory feedback to compensate and correct initial feedforward issues related to the specification of forces (Glazebrook et al., 2006). The implication is that the prolonged movement times often associated with autistic movements (Glazebrook et al., 2006) may be related to a strategy in which slower

movements allow them to overcome issues in feedforward control (Elliott et al., 2010).

As highlighted in *Figure 1.1*, another aspect of feedforward control relates to the use of an efference copy (Von Holst, 1954). During motor planning the generation of a motor command is used to specify the motor execution profile, as well as forming an efference copy for motor control. In this context, an efference copy provides a reference of the to-be-executed movement, which can be compared against the actual movement, thereby allowing early movement adaptation before afferent information can be processed (Elliott et al., 2010; Miall & Wolpert, 1996; Wolpert & Flanagan, 2001). This comparison can be used to make graded adjustments to the muscular forces being produced to drive the limb (e.g., towards a light switch), and as such allows an individual to accelerate or decelerate the limb as required (Elliott et al., 2010). As illustrated in *Figure 1.2*, it has been suggested that an individual engages in the aforementioned process of comparing the expected and actual efference in the interval between movement initiation and peak acceleration during a manual aiming movement (Elliott et al., 2010). Consequently, differences at this kinematic landmark, such as spatial variability, could be indicative of issues related to specification and/or timing of muscular forces in the early stages of an aiming movement (Elliott et al., 2010). When performing manual aiming movements to randomised target positions, autistic participants demonstrated significantly greater spatial variability at peak acceleration than control participants (Glazebrook et al., 2006). However, the authors did find that this significant difference in spatial variability was no longer present at peak velocity, which could suggest any errors earlier in the movement may have been compensated by functional online control using available sensory (e.g., vision) feedback. Consequently, these data suggest that the group difference was specifically related to issues in feedforward control,

potentially associated with motor planning, as well as a possible discrepancy between the actual and expected efference.

1.4 Motor Learning

Humans ability to perform motor behaviours and/or adapt to the constraints of their environment often occurs through a process of trial and error learning (Wolpert, Diedrichsen, & Flanagan, 2011). Over repeated trials, individuals make comparisons between the actual and predicted outcome of an action in order to generate feedback related to their performance. This feedback can then be used in an attempt to improve accuracy on subsequent trials. For example, if an individual attempts to reach and press a light switch, but instead finds that it was out of reach, they can use this information to make sure their starting position is closer to the switch on the next trial. As a result, the individual can develop and refine an internal action model by representing associations between the motor commands that drive the limb towards a specified movement goal (i.e., light switch), the environment that they are in and the sensory (e.g., vision and proprioception) consequences of limb movement (Krakauer & Shadmehr, 2007). Moreover, by continually engaging in this process sensorimotor adaptation (Wolpert et al., 2011; Wolpert & Flanagan, 2010) can occur, reducing motor variability and increasing accuracy. Not only do these internal action models underpin the sensorimotor control processing described above but it has also been suggested that social and communicative impairments in autism may be influenced by difficulties in developing skilled behaviours (Haswell et al., 2009; Mostofsky et al., 2006; Mostofsky & Ewen, 2011). For example, Mostofsky and colleagues (2006) demonstrated that autistic children showed increased errors when performing gestures to command, gestures with imitation and gestures with tool use. Consequently, motor learning and the formation of internal action models

has been examined in autism as well as the aforementioned differences in motor behaviour and control (Fournier et al., 2010; Gowen & Hamilton, 2013; Leary & Hill, 1996).

As described in previous sections, autistic individuals have been shown to be generally less accurate and more variable during locomotion (Calhoun et al., 2011; Rinehart, Tonge, et al., 2006; Vernazza-Martin et al., 2005) and manual aiming movements (J. Cook et al., 2013; Glazebrook et al., 2006; Hayes et al., 2018). However, the sensorimotor processes that underlie the formation of internal action models during sensorimotor learning seem to be operational (Gidley Larson, Bastian, Donchin, Shadmehr, & Mostofsky, 2008; Haswell et al., 2009; Hayes et al., 2018; Izawa et al., 2012). When autistic participants' vision was perturbed via a prism, they were able to adapt their motor output and reduce error during a ball throwing task (Gidley Larson et al., 2008). Following a baseline period where participants threw a ball to a target, they repeated the same task whilst wearing prism goggles that perturbed their vision to the right by 17°. Participants from both groups showed an immediate increase in error upon changing condition but adapted similarly, by reducing error across trials. Finally, participants returned to the non-perturbed condition and importantly, both groups demonstrated immediate after-effects (i.e., error increased). This finding shows that during the perturbed condition, both autistic and controlled participants successfully formed an internal action model that represented the expected sensory and motor consequences associated with that condition. Therefore, when returning to the control condition, this model was no longer accurate and as a result the immediate increase in error was observed. Furthermore, it has been shown that the learning of a three-segment movement sequence in autism is also similar to that of controls (Hayes et al., 2018). During an acquisition period, where knowledge-of-results was provided, autistic participants

modulated their motor output becoming more accurate and less variable. Importantly this adaptation was maintained in retention, providing evidence of learning. A group difference between the autism and control groups was however present throughout the study. Whether this difference was related to how participants structured the three-segment movement sequence was not examined, but the findings suggest that execution differences in autism are potentially related to issues in the sensorimotor control processes described above, and not a fundamental problem in the formation and refinement action models.

That said, how autistic individuals are able to generalise internal actions models does seem to be different (Haswell et al., 2009; Izawa et al., 2012; Marko et al., 2015; Mostofsky & Ewen, 2011; Nebel et al., 2016). The ability to generalise is reflected in how well an individual can execute an action associated with an existing internal action model under conditions (i.e., direction of movement) that differ to those in which it was developed (Shadmehr & Moussavi, 2000). As discussed in the subsection on sensory systems, autistic participants showed better performance when transferring a learned motor skill to an intrinsic coordinate where proprioceptive feedback was similar to that experienced during learning, than an extrinsic coordinate where the visual feedback was similar (Haswell et al., 2009). This potential prioritisation of proprioceptive feedback (Haswell et al., 2009; Izawa et al., 2012) could have important implications for how autistic individuals interact with their environment given the bi-directional links between perception and action (Prinz, 1997). It is therefore of interest that Haswell and colleagues (2009) also investigated whether a relationship was present between the extent to which autistic participants prioritised proprioceptive feedback and measures of autism severity (e.g., ADOS; SRS) and imitation ability. In all cases they found that the greater an autistic child's social impairment, the more they prioritised the proprioceptive

feedback. The implication is that although autistic participants can successfully develop new internal action models (Gidley Larson et al., 2008; Hayes et al., 2018), differences in sensorimotor integration and/or processing may occur (Haswell et al., 2009; Izawa et al., 2012). This is consistent with the finding of altered neural activity during motor learning in autism (Müller, Cauich, Rubio, Mizuno, & Courchesne, 2004; Müller, Kleinhans, Kemmotsu, Pierce, & Courchesne, 2003). For instance, Müller et al. (2004) found greater activation of the premotor cortex occurred during the later the stages of learning for autistic participants in comparison to controls, which may not necessarily support effective internal action model formation and motor performance (Müller et al., 2004). Similarly, differences in motor ability in autism have been associated with deformation of the basal ganglia (Qiu, Adler, Crocetti, Miller, & Mostofsky, 2010), an area that alongside the motor cortex (Eliassen, Souza, & Sanes, 2001), and the cerebellum is thought to be responsible for motor learning processes (Doyon et al., 2009; Shadmehr & Krakauer, 2008). Overall, the extant evidence indicates that autistic participants do show the ability to develop and refine new internal action models (Gidley Larson et al., 2008; Hayes et al., 2018), but they may be autism specific (J. Cook, 2016; Mostofsky & Ewen, 2011) due to differences in sensorimotor integration and/or processing (Haswell et al., 2009; Izawa et al., 2012) .

1.5 Sensorimotor processing during action-observation

As explained above, autistic individuals have been shown to be able to learn novel movements (Gidley Larson et al., 2008; Hayes et al., 2018) via the active engagement of the peripheral motor system. This requires them to represent associations between self-generated motor commands, the sensory consequences of said motor commands, and the environment in which the individual is interacting

(Krakauer & Shadmehr, 2007). Another means of engaging in this sensorimotor process, not yet discussed, is via action-observation. This is when an individual observes a model performing an action (e.g., pressing a light switch) with the intention to accurately replicate it. Here, a higher-order action-goal (e.g., to press the switch) and the lower-level kinematics properties (e.g., velocity of hand), which constrain the means of achieving the action goal, are encoded in a sensorimotor system directly linking perception and action (Brass & Heyes, 2005; Jeannerod, 1994; Prinz, 1997). This then facilitates the development of a new internal action model, enabling the accurate reproduction of the perceived biological movement properties of the model.

A major neurophysiological mechanism that forms part of the sensorimotor system involved in perception-action coupling is the mirror neuron system (or action-observation network), defined as the regions of the inferior frontal gyrus, inferior parietal lobule and premotor cortex. These areas have been shown to be active during both execution and observation (Buccino et al., 2004; Iacoboni et al., 1999; Rizzolatti & Craighero, 2004; Vogt et al., 2007) and allow a visual input to be processed and mapped to a motor output (Hamilton, 2015). Moreover, this system is suggested to enable us to interpret others' actions (Jeannerod, 2001) and supports socio-cognitive function (Rizzolatti & Sinigaglia, 2010). For example, in a study where children observed a model bring food to their mouth (Cattaneo et al., 2007), it was shown that the children would demonstrate significant activation of the muscles responsible for opening the mouth whilst the model was still reaching. This finding indicates that the children were able to infer the model's intention prior to goal attainment. Furthermore, this system is suggested to be biologically tuned (Press, 2011) to the kinematic properties of a model (Candidi, Urgesi, Ionta, & Aglioti, 2008), as well as the form of any observed stimulus (Brass, Bekkering, & Prinz,

2001). This has been shown behaviourally by Kilner, Hamilton, and Blakemore (2007) who, using an interpersonal execution task, found participants demonstrated a greater motor interference effect when participants observed stimuli that moved with biological kinematics in comparison to when the observed model that moved with a constant velocity. Additionally, Candidi et al. (2008) used transcranial magnetic stimulation (TMS) to show that virtual lesions to the ventral premotor area attenuated a participant's ability to discriminate stimuli with biologically possible kinematic properties. The virtual lesions, however, did not affect the discrimination of stimuli with non-biologically possible properties demonstrating that this area of the action-observation network shows differential activation when observing biological stimuli.

The ability to perceive biological motion has also been shown to be functional in autism (J. Cook et al., 2013; Cusack, Williams, & Neri, 2015; Hayes et al., 2018; Saygin, Cook, & Blakemore, 2010; Wild, Poliakoff, Jerrison, & Gowen, 2012). Using point-light displays to examine action-perception, Cusack et al. (2015) showed similar levels of biological motion perception between autism and control participants across several experiments. They did suggest, however, that although the signals for interpreting others' actions are intact, the autistic participants may not be able to use this information as effectively as control participants during 'real-life' social interactions. Consistent with this interpretation is the work of Nackaerts et al. (2012), who found that autistic participants were less accurate than controls in recognising biological motion from point light displays, with differences in the processing of facial expressions having also been shown (Harms, Martin, & Wallace, 2010). These may be examples of such areas of 'real-life' social interactions where differences in biological motion processing in autism occur. Moreover, autistic participants have been reported to display a specific difficulty imitating the

kinematic properties of biological motion (DeMyer et al., 1972; Hayes, Andrew, Elliott, Gowen, & Bennett, 2016; Hobson & Lee, 1999; Rogers, Bennetto, McEvoy, & Pennington, 1996; Stewart, McIntosh, & Williams, 2013; Wild et al., 2012), suggesting that these kinematic properties may be processed differently. This could potentially be a consequence of altered sensorimotor integration and/or processing in autism which leads to the development of autism-specific internal action models (J. Cook, 2016; Mostofsky & Ewen, 2011). If correct, this could result in a mis-match between autistic individuals sensorimotor system, which has been previously characterised by an altered kinematic profile (J. Cook et al., 2013), and the observed actions of a neurotypical model that they are imitating. This mis-match could then impact upon the sensorimotor processing involved in interpreting others (Jeannerod, 2001).

1.6 Imitation

In humans the ability to copy the actions of others is acquired very early in life (Carpenter, Akhtar, & Tomasello, 1998; Heyes, 2001), and is fundamental to our cognitive, social and cultural development. Thus, given that difficulties in social interaction and communication are synonymous with autism, imitation is an area that has seen extensive study. Edwards (2014) conducted a meta-analysis that revealed across the 53 studies reviewed, autistic participants were an average of 0.81 standard deviations less accurate in imitation tasks than controls. Moreover, autistic participants' imitation performances were shown to have a significant negative relationship with their scores on the autism diagnostic observation schedule (ADOS). This relationship suggests that the severity of autistic symptoms could impact on the imitation differences observed in autistic individuals.

One of the early studies to investigate imitation in autism was conducted by DeMyer et al. (1972). They found children with autism were more accurate at motor-object imitation, where they copied an experimenter's use of an object, than body imitation, where they copied the experimenter performing movements such as hopping or touching their nose. This specific body imitation difference in autism has since been suggested to be potentially underpinned (Williams, Whiten, Suddendorf, & Perrett, 2001) by the previously described differences sensorimotor processing (Bernier, Dawson, Webb, & Murias, 2007; Dapretto et al., 2006; Oberman et al., 2005; Théoret et al., 2005; Williams et al., 2006). For example, during the imitation of facial expressions, autistic participants have been reported to exhibit lower levels of mirror activity in the pars opercularis compared to control participants despite both groups' achieving successful imitation (Dapretto et al., 2006). Similarly, Williams et al. (2006) showed differential behavioural and neural effects during a functional magnetic resonance imaging (fMRI) study that examined neural activity during motor imitation. Both groups successfully imitated the observed stimuli, but the autism group exhibited neural activation differences across a broad action-observation network, with a key difference being the anterior parietal region.

The type of imitation protocol used by Williams et al. (2006) is referred to as automatic imitation. Here, individuals spontaneously copy a stimulus when the observer unintentionally produces an automatic response to a stimulus, copying its features (Heyes, 2011). For example, the observation of an incongruent biological motion stimulus (e.g., middle finger being raised) during execution (e.g., raising index finder) should produce an interference effect as it is automatically mapped within a participant's motor system. This effect in autism would therefore provide evidence of functional sensorimotor processing, indicating that action-observation has direct, automatic influence on motor execution (Brass et al., 2001), rather than

imitation being modulated by an altered processing system (Williams et al., 2001). Importantly, similar automatic imitation effects have been reported in autistic and control participants (Bird, Leighton, Press, & Heyes, 2007; Edey et al., 2016; Hamilton et al., 2007; Press, Richardson, & Bird, 2010; Schulte-Rüther et al., 2017; Sowden, Koehne, Catmur, Dziobek, & Bird, 2016; Spengler et al., 2010). For example, when performing a predetermined hand-movement in response to a compatible stimulus (same movement as participant), both autistic and control participants showed faster response times compared to when responding to an incompatible stimulus (different movement to participant) (Bird et al., 2007). The implication is that lower-level sensorimotor processes underpinning a direct link between perception and action (Brass & Heyes, 2005; Jeannerod, 1994; Prinz, 1997) are functional in autism.

Similar to automatic imitation is the phenomena of motor contagion (Blakemore & Frith, 2005). One means of examining motor contagion is via an interpersonal execution task where the participants perform sinusoidal arm movements (e.g., horizontal) whilst observing a model perform either a congruent (e.g., horizontal) or incongruent (e.g., vertical) arm movement (Kilner et al., 2007; Kilner, Paulignan, & Blakemore, 2003). In control participants it has been consistently shown that greater interference effects, such as orthogonal deviation, occur when observing incongruent actions (Kilner et al., 2007; Kilner et al., 2003; Roberts, Hayes, Uji, & Bennett, 2014). However, studies in autism have been less consistent. Gowen, Stanley, and Miall (2008) found typical interference effects in autism using protocols that involved both non-social (white-dot) and social (gender-matched experimenter) models. However, J. Cook, Swapp, Pan, Bianchi-Berthouze, and Blakemore (2014) did not observe motor contagion in an autism group. The authors suggested that one reason for this discrepancy in findings may be related to

Gowen et al.'s (2008) protocol, which required participants to perform one of two possible movements to a cue, rather than one as in their protocol. They suggest that participants may have prepared the incorrect movement which caused an interference effect, rather than any motor contagion effect. However, where contagion is reported to have occurred several factors have been suggested to contribute to the effect including the spatial direction of the observed stimulus (Hardwick & Edwards, 2012; Kilner et al., 2007), as well as the influence of incongruent end-points (Gowen et al., 2008; Stanley, Gowen, & Miall, 2007). A study by Roberts et al. (2014) investigated the above factors and found increased contagion when participants were presented with a curvilinear stimulus that featured an incongruent trajectory, but congruent end-points. This suggests participants may, in line with the goal-directed theory of imitation (GOADI; Bekkering, Wohlschlager, & Gattis, 2000), be creating a hierarchy of goals in relation to how important they are for imitation.

Likewise, true imitation, whereby the participant aims to imitate the goal of an observed action, as well as the means by which it was achieved, has also been investigated in autism (Vivanti & Hamilton, 2014). In such a protocol, it is of particular interest to examine how individuals form a hierarchy of goals that applies different priorities to outcome achievement (e.g., pressing the light switch) and movement form (e.g., how fast they moved the limb). Hobson and Lee (1999) examined whether autistic children were able imitate the style of an observed action. Using novel tasks, such as strumming a stick over a pipe rack, they modulated the style in which the action was performed. In the example of the stick and pipe rack, the experimenter would either produce a harsh strumming action, producing a loud sound, or a gentle action, which produced a softer sound. They found that the autistic children were significantly less likely to imitate the style of an observed action than

their control counterparts. They were, however, on average able to successfully imitate the goal (i.e., strum the pipe rack with the stick) of the observed actions. Since this work, several other studies have also examined the role of goals during imitation in autism (Hamilton et al., 2007; Salowitz et al., 2013; Wild et al., 2012). In a study by Hamilton et al. (2007), participants sat opposite an experimenter who performed hand movements to target locations. Participants had to imitate these movements across two blocks of trials, one where the target locations were indicated by markers on the table, and one where these markers were removed. They also found that autistic participants were able to imitate the goal of an action similarly to controls. Wild and colleagues (2012) found a similar result in the accuracy of goal-directed imitation. However, they also found that only the control participants modulated their movement kinematics in the goal-less condition in order to accurately imitate the means of the observed action. Eye movement analysis revealed that autistic participants spent significantly less time in smooth pursuit and more time fixating on the targets than controls regardless of whether goals were present in the stimuli, suggesting that autistic participants may rely on goal-directed imitation strategies (Wild et al., 2012).

The use of goal-directed strategies may therefore contribute to differences in the imitation of biological kinematics in autism (DeMyer et al., 1972; Hayes, Andrew, et al., 2016; Hobson & Lee, 1999; Rogers et al., 1996; Stewart et al., 2013; Wild et al., 2012). Hayes et al. (2015) adopted a protocol that attempted to minimise goal-directed strategies by presenting stimuli with and without end-point goals in a randomised order. To examine the imitation of biological kinematics they presented stimuli with three different velocity profiles (i.e., atypical, typical, constant velocity). Both the typical and atypical velocity profiles were biologically plausible movements, but importantly the atypical profile was novel and would not be part of

the participants' existing sensorimotor repertoire. Accordingly, imitation of the atypical model could not simply occur by rescaling a typical upper-limb movement from memory. It was found that only the control group was able to accurately imitate the atypical profile, although the autism group did successfully reproduce the stimulus movement time. The authors therefore suggested that imitation differences may be related to selective attention, or differences in the sensorimotor processing, and/or the motor ability of the autistic participants. Examples of these sensorimotor differences may include motor planning (Hughes, 1996) and differences in action model formation (Haswell et al., 2009; Mostofsky & Ewen, 2011), discussion of which can be found in the previous sections.

1.7 Aims of Thesis

As outlined in the above sections, autism is a developmental condition primarily associated with difficulties in social communication and interaction, as well restricted and repetitive behaviours and interests (American Psychiatric Association, 2013). In addition to these core components, motor differences have also been widely reported in autism (for a review see Fournier et al., 2010). Differences in sensorimotor integration have led to the suggestion of an autism specific sensorimotor system (J. Cook, 2016; Mostofsky & Ewen, 2011). This system may lead to an atypical personal point of reference (i.e., autistic sensorimotor system) impacting the development of internal action models, which consequently influences motor execution and the perception and prediction of others during social interaction (J. Cook, 2016). The current thesis aims to expand upon the understanding of sensorimotor integration in autism. To this end, three experiments (chapters three, four, five) will be conducted using behavioural methods (see below) that permit a comparison of autistic and neurotypical control participants. In addition

to this, an experiment (chapter two) will also be conducted to determine suitable data collection and analysis techniques.

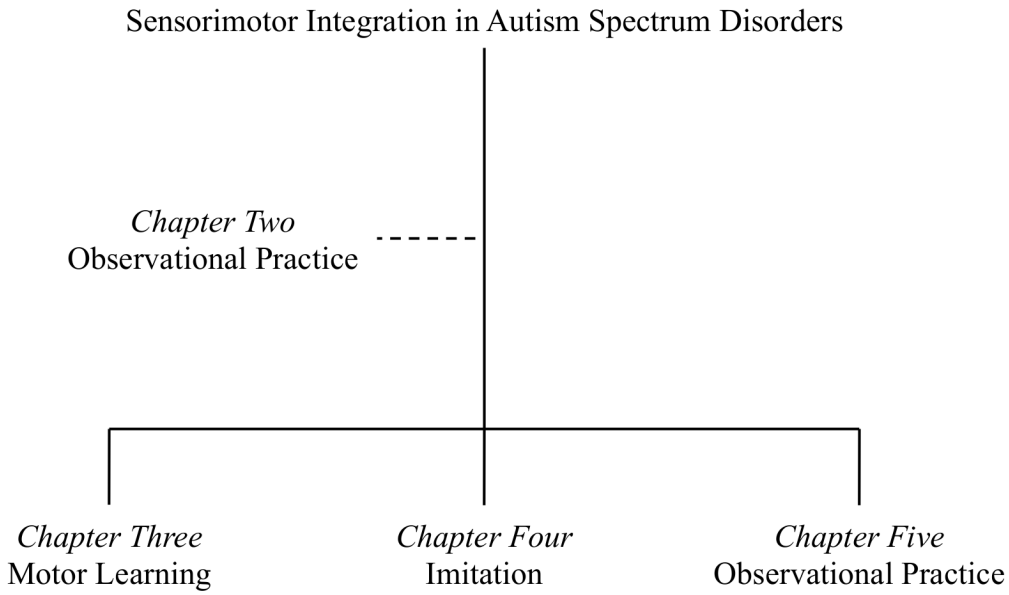

Figure 1.3: Overview of experimental chapters.

Chapter Two

The aim of chapter two is to investigate the effect of stimulus-response (S-R) compatibility (Hommel & Lippa, 1995) on the representation of atypical biological kinematics during observational practice. In order to interact with their environment, humans are often required to learn novel movements and skills. One means of engaging with this process is via observational practice, where sensorimotor learning takes place via the repeated observation of a model (Bird & Heyes, 2005; Bird, Osman, Saggerson, & Heyes, 2005; Osman, Bird, & Heyes, 2005). Observational practice is said to enable the formation of internal action models without actively engaging the peripheral motor system via a common-coding system linking perception and action (Brass & Heyes, 2005; Jeannerod, 1994; Prinz, 1997). This system has been shown to be biologically tuned, with participants being able to learn movements with both typical and atypical biological kinematics during observational

practice (Hayes, Dutoy, Elliott, Gowen, & Bennett, 2016; Hayes, Elliott, & Bennett, 2010, 2013; Hayes, Roberts, Elliott, & Bennett, 2014; Hayes, Timmis, & Bennett, 2009; Roberts, Bennett, Elliott, & Hayes, 2015). Previous work, however, did not control for the influence of spatial stimulus-response (S-R) compatibility (Heyes, Bird, Johnson, & Haggard, 2005). Accordingly, it may be possible that the spatial position of peak velocity was encoded during action-observation rather than the movement kinematics (Hommel & Lippa, 1995). As a result the experiment in chapter 2 aims to determine whether observational practice of atypical biological motion kinematics is underpinned by encoding spatial positions of kinematic landmarks (Hommel & Lippa, 1995), or if the atypical biological motion kinematics of the model itself are indeed encoded (Hayes et al., 2014). The experiment will also provide experience with the experimental procedures and equipment to be used in the later experiments of this thesis. Moreover, if the atypical kinematics represented during observational practice, it will demonstrate the efficacy of this methodology for use in autism (chapter five).

Chapter Three

Chapter three will examine motor learning and sensorimotor control processes in autism. Although the movements produced by autistic participants are generally less accurate and more variable in autism than neurotypical controls (J. Cook et al., 2013; Elliott et al., 2010; Glazebrook et al., 2006; Glazebrook et al., 2008; Li, Sharma, Meng, Purushwalkam, & Gowen, 2017), the formation of internal action models has been shown to be operational (Gidley Larson et al., 2008; Hayes et al., 2017). Execution differences in autism have been suggested to be related to problems occurring downstream during sensorimotor integration. For example, Glazebrook et al. (2006) found that autistic participants showed significantly greater

spatial variability at peak acceleration when compared to control participants. The period between movement initiation and peak acceleration is often associated with feedforward control, whereby participants compare the expected and actual efference and adjust their muscular forces to accelerate or decelerate the limb as required (Elliott et al., 2010). The implication is that these processes may be altered in autism. Extending upon previous work that examined discrete aiming to a single target in autistic participants (Glazebrook et al., 2006; Glazebrook et al., 2008; Glazebrook et al., 2009; Nazarali et al., 2009), this chapter will examine motor execution using a three-segment motor sequence task (Hayes et al., 2018). Overall timing error, as well as relative timing (i.e., how participants structure the motor sequence) will be examined to further investigate the formation of internal action models in autism and how the sensorimotor systems of both autism and control participants are constrained by the spatio-temporal characteristics of the task. Furthermore, a detailed kinematic analysis of spatial variability at key kinematic landmarks (i.e., peak acceleration, peak velocity) will be conducted for each segment in order to investigate feedforward and feedback sensorimotor control processes in autism. If differences in sensorimotor control are related to the specificity of the autistic sensorimotor system (J. Cook, 2016), it is predicted that differences in spatial variability (Glazebrook et al., 2006) will persist across both acquisition and retention and in all three movement segments, independent of any learning effects.

Chapter Four

Chapter four aims to examine sensorimotor planning and integration in autism during imitation learning. Imitation differences between autistic and neurotypical participants have been suggested to be associated with altered sensorimotor processing (Williams et al., 2001), although work on automatic

imitation has suggested this processing is functional in autism (Bird et al., 2007; Edey et al., 2016; Hamilton et al., 2007; Press et al., 2010; Schulte-Rüther et al., 2017; Sowden et al., 2016; Spengler et al., 2010). That said, autistic individuals are reported to show a specific difficulty imitating the lower-level biological kinematic properties of an observed action (DeMyer et al., 1972; Hayes, Andrew, et al., 2016; Hobson & Lee, 1999; Rogers et al., 1996; Stewart et al., 2013; Wild et al., 2012). For example, Hayes and colleagues (2016) found both autistic and control participants similarly imitated a model with typical kinematics, but the autistic group were significantly less accurate than control group when imitating atypical kinematics. They concluded that differences in sensorimotor integration and/the motor system may be one possible explanation for imitation deficits in autism (Hayes, Andrew, et al., 2016). In chapter four, both atypical and typical models will be presented in a consecutive, fixed trial order during acquisition. As sensorimotor information from trial *n* (i.e., atypical model) will be similar to trial *n+1* (i.e., atypical model) it should enable comparison of the expected and actual sensorimotor consequences from trial *n* to facilitate the planning of trial *n+1* (Elliott, Helsen, & Chua, 2001; Wolpert et al., 2011). Eye movements will also be recorded to control for visual attention (Wild et al., 2012). To investigate whether a fixed trial order in an acquisition phase does facilitate the imitation of atypical biological kinematics in autism, the change in participants behaviour will be compared between a pre-test and post-test in which trials (atypical and typical) are presented in random order. If differences in sensorimotor integration and/the motor system are related to imitation differences in autism (Hayes, Andrew, et al., 2016), the fixed-trial order is expected to result in more accurate imitation of the atypical model in the post-test than that of the participant's baseline performance in the post-test.

Chapter Five

The aim of chapter five is to investigate whether autistic individuals can reproduce atypical biological kinematics following observational practice. Like chapter four, this chapter will examine the reported specific difficulty in imitating lower-level biological kinematic properties in autism (DeMyer et al., 1972; Hayes, Andrew, et al., 2016; Hobson & Lee, 1999; Rogers et al., 1996; Stewart et al., 2013; Wild et al., 2012). As previously stated, sensorimotor integration issues related to motor planning and execution have previously been suggested to affect imitation accuracy in autism (Hayes, Andrew, et al., 2016). Therefore, chapter five will use an observational practice protocol where sensorimotor learning can occur via the repeated observation of a model without engaging the peripheral motor system (Bird & Heyes, 2005; Bird et al., 2005; Osman et al., 2005). This methodology is intended to isolate the reproduction of atypical biological kinematics to the activation of a common-coding system linking perception and action (Brass & Heyes, 2005; Jeannerod, 1994; Prinz, 1997), without interference from an autism specific motor system (J. Cook, 2016; Mostofsky & Ewen, 2011) and associated issues related to motor planning and execution (Cattaneo et al., 2007; Fabbri-Destro et al., 2009; Glazebrook et al., 2006; Glazebrook et al., 2008; Glazebrook et al., 2009; Hughes, 1996; Nazarali et al., 2009; Rinehart, Bellgrove, et al., 2006; Rinehart et al., 2001). The mirror neuron system, defined as the regions of the inferior frontal gyrus, inferior parietal lobule and premotor cortex, has been shown to be active during both execution and observation (Buccino et al., 2004; Iacoboni et al., 1999; Rizzolatti & Craighero, 2004; Vogt et al., 2007) and allows a visual input to be processed and mapped to a motor output, facilitating imitation (Hamilton, 2015). Although activation of these areas has been suggested to be altered in autism (Dapretto et al., 2006), the autism group is expected to modulate their motor output following

observational practice, in line with findings in automatic imitation (Bird et al., 2007; Edey et al., 2016; Hamilton et al., 2007; Press et al., 2010; Schulte-Rüther et al., 2017; Sowden et al., 2016; Spengler et al., 2010). Importantly, a follow up imitation protocol, will then be used to investigate whether the contributions of reafference and sensorimotor integration negatively impact the imitation of a learned movement in autism.

Chapter Six

The final chapter of this thesis will aim to summarise the key findings of the five experimental chapters outlined above. These findings will be critically evaluated with regards to the current literature, as well as any theoretical implications. The direction of future research will be discussed in addition to the applications for these findings within the field.

2 Chapter Two: Atypical biological kinematics are represented during observational practice.

2.1 Introduction

When interacting with their environment, and with others, humans are often required to learn novel movements. One route via which humans engage in sensorimotor learning is known as observational practice, and occurs when a person repeatedly watches a model before reproducing the observed action. The efficacy of observational practice has been demonstrated experimentally in a number of studies; for example, compared to control groups without an opportunity to learn, observational practice groups acquired knowledge of a sequence of finger movements having merely watched a model perform the sequence of movements (Bird & Heyes, 2005; Bird et al., 2005; Osman et al., 2005). In addition to leading to the acquisition of the observed motor behaviour, observational practice also produces similar adaptation in the cortical sensorimotor system (i.e., action-observation network; Cross, Kraemer, Hamilton, Kelley, & Grafton, 2009). These findings show that even though the peripheral motor system is not engaged in the observed motor task during observational practice (e.g., the relevant limb is at rest), a sensorimotor representation of the action is developed by engaging a common-coding system linking perception and action (Brass & Heyes, 2005; Jeannerod, 1994; Prinz, 1997).

Direct activation of the sensorimotor system during the observation of actions is said to be underpinned by processes preferentially tuned to biological motion (Press, 2011). As well as facilitating socio-cognitive functioning during interactions between people (J. Cook et al., 2013; Press, Cook, Blakemore, & Kilner, 2011), biological tuning is important for the acquisition of novel motor actions during observational practice (Bird & Heyes, 2005). Biological tuning has previously been confirmed across a series of behavioural studies where participants observe a series of model stimuli that depict typical or atypical human biological

kinematics (Hayes, Dutoy, et al., 2016; Hayes et al., 2010, 2013; Hayes et al., 2014; Hayes et al., 2009; Roberts et al., 2015). Typical kinematics had a movement profile where peak velocity occurred at approximately 50% of the trajectory, which is consistent with goal-directed upper-limb aiming movements (Elliott et al., 2010). Atypical kinematics were novel, and displayed peaks occurring at 18% (Hayes, Dutoy, et al., 2016) or 77% (Hayes et al., 2014) of the movement trajectory. From a theoretical perspective, the presentation of atypical kinematics is fundamental for understanding the contribution of low-level sensorimotor processes during observational practice. For example, if a model is presented that has typical kinematics it cannot be ruled out that imitation is based on a representation of the movement speed, as opposed to a representation of the underlying biological motion kinematics. In the former case, the feedforward contribution to motor execution would have been associated with rescaling a pre-existing motor representation of a familiar and meaningful movement based on higher-order semantic processes (Rumiati et al., 2005). In contrast, imitation of atypical kinematics cannot be solved by merely recruiting an existing sensorimotor representation; the sensorimotor system needs to be configured during observational practice based on a representation of the observed kinematics.

Although this previous work demonstrated biological specificity, it did not control for the influence of spatial stimulus-response (S-R) compatibility (Heyes et al., 2005). Therefore, it remains a possibility that the spatial position of peak velocity could have been encoded during action observation rather than the movement kinematics *per se* (Hommel & Lippa, 1995). To better locate processing of biological motion within sensorimotor processes, S-R compatibility can be controlled by arranging the stimulus and response in an orthogonal (e.g., stimulus hand vertical; responding hand horizontal) orientation. Indeed, using these

techniques during studies of automatic imitation, which recruits similar sensorimotor processes as observational practice (Heyes, 2011), motor responses are facilitated in compatible compared to incompatible trials, thus confirming direct activation of motor representations during action-observation which is not confounded by spatial S-R compatibility (Bertenthal, Longo, & Kosobud, 2006; Catmur & Heyes, 2011; Heyes et al., 2005; Press, Bird, Walsh, & Heyes, 2008).

Based on this methodology, the current study investigated S-R compatibility on the reproduction of atypical biological kinematics following observational practice. Participants in a *compatible group* and *incompatible group* observed a model (a single dot) with the intention to reproduce the movement trajectory following observational practice. For the *compatible group* the model was observed moving in a left to right direction on a monitor, whereas the *incompatible group* observed the model moving in a right to left direction. A control group did not engage in observational practice. In a post-test, the experimental groups were both instructed to reproduce the modelled movement(s) in a left to right direction. If the reproduction of atypical biological kinematics is underpinned by direct activation of sensorimotor processes, comparable post-test performance between the two experimental groups is expected. If, however, reproduction is mediated by S-R compatibility associated with spatial orientation, the *compatible group* should perform more accurately than the *incompatible group*. Finally, it is expected that both experimental groups will show an advantage of observational practice compared to the control group when reproducing atypical biological kinematics.

2.2 Methods

Participants

Sixty participants (44 males; 16 females; mean age of 22 years) with normal, or corrected to normal vision, were provided with an information sheet and consented to be a volunteer in the study. Participants were randomly assigned to a *compatible group*, *incompatible group*, and *control group*. The study was designed in accordance with the 1964 Declaration of Helsinki and approved by the local research ethics committee.

Apparatus and Stimuli

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 555 mm. The monitor was connected to a PC (HP Compaq 8000 Elite), which also recorded input of a hand-held stylus on a graphics tablet (Wacom Intuos Pro XL). Experimental stimuli were generated using COGENT toolbox (developed by John Romaya at the Laboratory of Neurobiology at the Wellcome Department of Imaging Neuroscience) and implemented by MATLAB (Mathworks Inc.).

Two non-human agent models were created by a human volunteer performing *typical* (used in pre-test) and *atypical* (used in the observational practice phase) horizontal movements using a hand-held stylus on a graphics tablet (*Figure 2.1.A*). The stylus movement was represented as a white-dot (diameter = 6 mm) on the computer monitor, and traversed from the left-hand start-position (red-dot, diameter = 12 mm) to the right-hand end-position located at an amplitude of 200 mm. The total movement duration was exactly 1700 ms. For both models, raw position data were first filtered using a low pass 4th order autoregressive filter with an 8 Hz cut-off. Data were then differentiated using a three-point central difference algorithm to obtain velocity. The *typical* model reflected an exemplar trial, and thus

displayed a typical (Elliott et al., 2010; Flash & Hogan, 1985) bell-shaped velocity profile (dashed trace in *Figure 2.1.B*) with a peak of 0.19 mm/ms that occurred at 44% of the movement duration. For the *atypical* model (black trace in *Figure 2.1.B*), peak velocity was 0.33 mm/ms and occurred at 18% of the movement duration. The method of using a human volunteer to generate both models was important because it ensured the kinematics were biological and reproducible by participants (Hayes, Dutoy, et al., 2016). This did result in movement deviation in the x and y axes, however the latter was minimal (i.e., perpendicular deviation) as confirmed by a root mean square error of 0.9 mm for the *atypical* model and 1.55 mm for the *typical* model.

Procedure

The experiment consisted of a pre-test, observational practice phase, and a post-test. In the pre-test, the control group received exactly the same instructions as the experimental groups, which were to watch the monitor and focus on watching how the model moved. Following an observation, all participants were instructed to imitate how the model moved by using the stylus on the tablet. All participants observed the *typical* model, however no specific information was provided to the groups regarding the nature of model, nor was feedback regarding imitation performance provided. The pre-test procedure familiarised participants with the spatiotemporal relationship between the stylus movement on the graphics tablet and cursor movement on the screen, and quantified baseline motor behaviour associated with performing typical goal-directed movements.

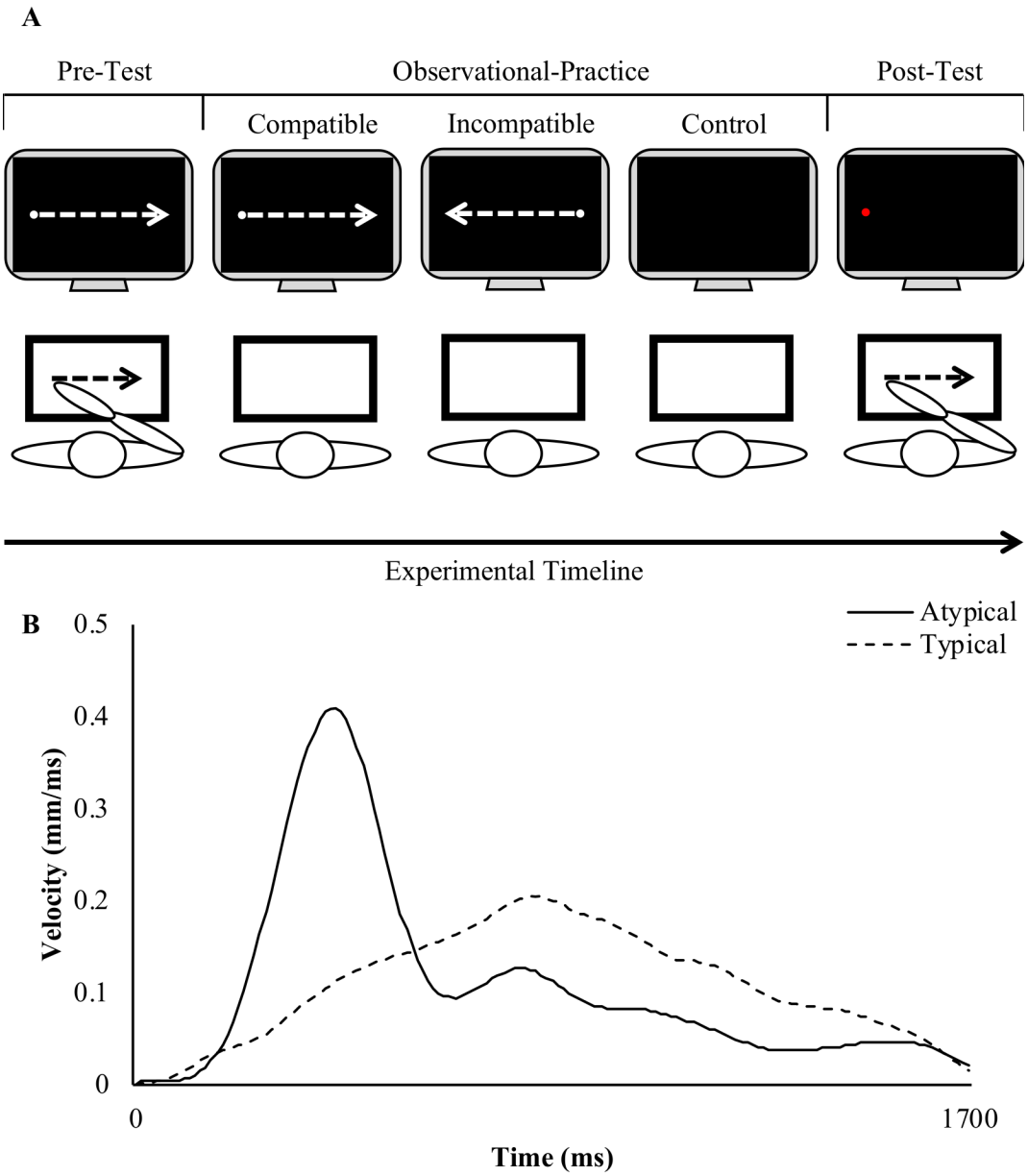

Figure 2.1: (A) A schematic representation of the experimental design as a function of phase and group. The black outlined rectangle represents a graphics tablet. The white circle displayed on the CRT monitor represents the model. The single-segment movement is depicted by the arrow (i.e., from the start-position to the end-position). (B) Displacement time-series displaying typical (dashed trace) and atypical (black trace) velocity models.

The observational practice phase consisted of 30 consecutive action-observation trials (*Figure 2.1.A*). The *compatible group* observed the *atypical* model as it moved rightwards, while the *incompatible group* observed the same *atypical* model, but moving leftwards. Having reversed the direction of motion, peak velocity

still occurred at 18% of the movement duration. Both experimental groups were instructed to observe the model with the intention to execute a movement in the post-test that reproduced the *atypical* movement trajectory (Hayes et al., 2014). As per the pre-test, the experimental groups received no specific information regarding the nature of modelled kinematics, nor was feedback regarding imitation performance provided. For each trial during this phase, the cursor first appeared as a stationary white-dot within a start-position on either the left-side (compatible) or right-side (incompatible) for a duration of 1000 ms. The cursor would then move following the *atypical* movement trajectory for a movement duration of 1700ms. Finally a blank screen would be shown during the inter-trial interval for 3000 ms, giving a total trial duration of 4700 ms. Throughout the observational practice phase the control group observed a blank screen for an equal duration to the experimental groups completing thirty trials (*Figure 2.1.A*).

In the post-test, the experimental groups performed 10 trials that required them to recall and execute a movement that reproduced the profile of the observed *atypical* model. Importantly, all movements commenced from a start-position located at a left-side start-position and ended on the right-side of the screen. The *control group* executed a movement as per the pre-test. No feedback regarding imitation performance was provided to any group.

Data Reduction

The analysis was focused on the primary movement (i.e., x-axis data) and did not take into account minimal deviation in perpendicular axis (i.e., RMSE < 1.5 mm), which was most likely an incidental result of anatomical constraints rather than intentional imitation (Hayes, Dutoy, et al., 2016). First, the start and end of the movement within the x-axis position data were identified. The start was defined as

the moment the centre of the cursor moved beyond the perimeter of the start-position circle, and the end equated to the moment the participant clicked the upper-button on the stylus. Next, for each trial the position data were filtered using a low pass 4th order autoregressive filter with an 8 Hz cut-off. Data were then differentiated using a three-point central difference algorithm to obtain velocity. Finally, extracted *percentage-time-to-peak-hand-velocity (tPHV)* from each trial.

Data Analysis

The effect of observational practice on motor performance was examined by comparing *tPHV* at post-test as a function of group. To minimise the impact of initial group differences resulting from random assignment, and to statistically control for the baseline effects from imitating the typical model that is not the primary interest of the analysis, the pre-test data was used as a covariate (ANCOVA). Post hoc pairwise comparisons were conducted using Bonferroni corrections. Alpha was set at $p < 0.05$, and partial eta squared (η_p^2) expressed the size of the effect. In addition, and to account for issues with null hypothesis statistical testing (Jarosz & Wiley, 2014; Masson, 2011; Rouder, 2014; Wagenmakers, 2007), the BayesFactor package (Morey & Rouder, 2015) using RStudio v. 1.0.44 was used to run three separate Bayesian ANCOVAs. This involved calculating Bayes factors (BF_{01}) to estimate the posterior probability through an odds ratio for the null/alternative hypothesis (a value of 1 means they are equally likely; larger values indicate more evidence for the null; smaller values indicate more evidence for the alternative).

2.3 Results

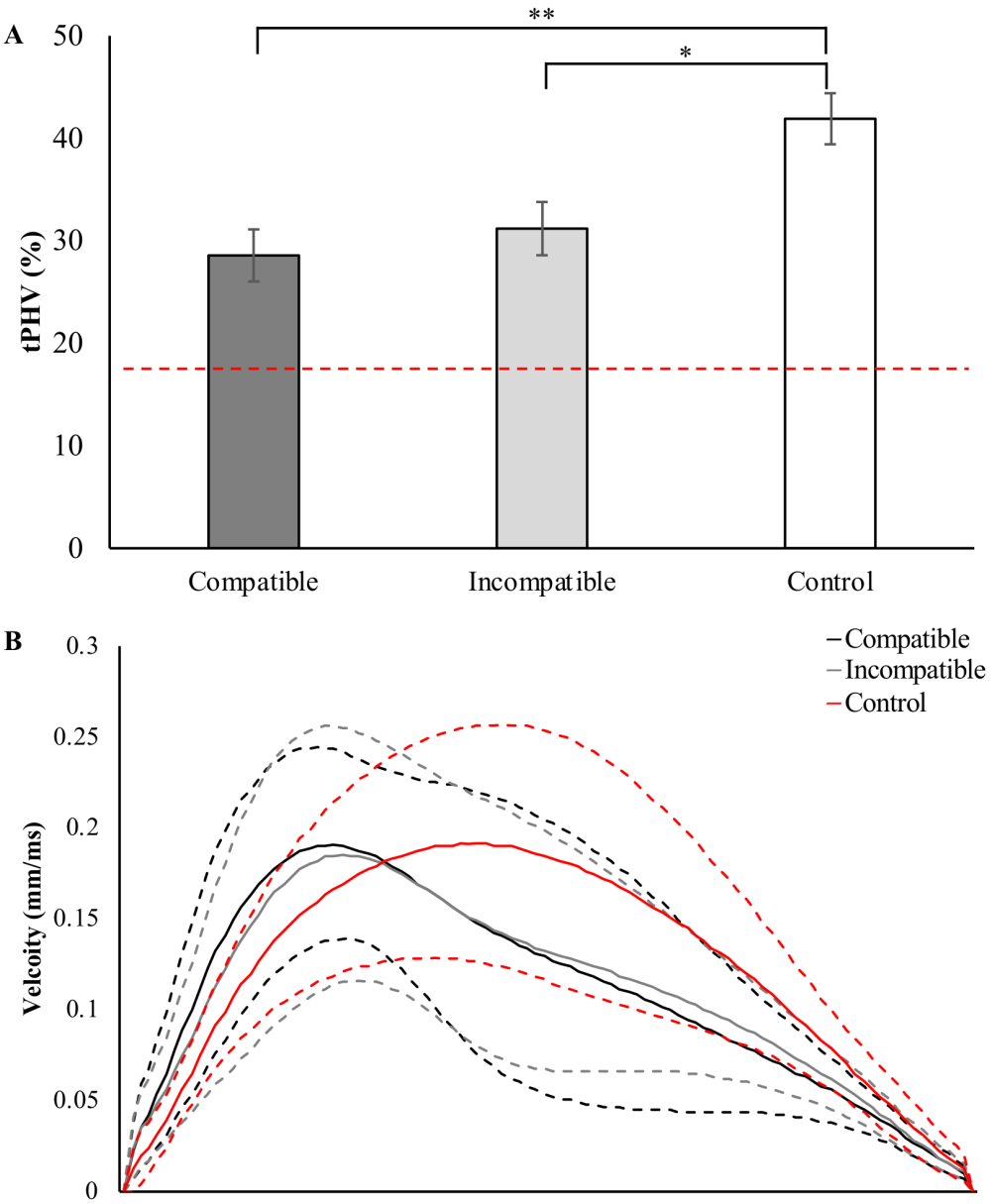

Figure 2.2: (A) Percentage-time-to-peak-hand-velocity for the post-test (error bars represent standard error of the mean) presented as a function of group. Dashed line represents the atypical model. ** $p < 0.01$; * $p < 0.05$. (B) Mean (dashed lines indicate standard deviation of the mean) velocity traces of trial performance in the post-test for the compatible (black trace), incompatible (grey trace), and control (red trace) groups.

ANCOVA indicated a significant main effect of group for *tPHV* [F (2,56) = 7.871, $p = 0.001$, $\eta_p^2 = 0.219$]. Post hoc tests indicated the *tPHV* reproduced by the

compatible (M = 28%) and *incompatible* (M = 31%) groups were comparable (*t = 0.97, p* > 0.05; BF_{01} = 2.25). The exemplar data presented in *Figure 2.2.B* illustrates how the two experimental groups reproduced a peak velocity that occurred early in the movement trajectory, in a similar manner to the atypical model (*Figure 2.1.B*). The difference in *tPHV* between the *compatible group* and the *control group* was 12 units (*t* = 3.84, p < 0.01; BF_{01} = 0.004), and 9 units between the *incompatible group* and the *control group* (*t* = 2.73, *p* < 0.05; BF_{01} = 0.03). Notably, the occurrence of *tPHV* for the control group (M = 40%) was towards the midpoint of the trajectory (*Figure 2.2.B*), and thus similar to the typical model (*Figure 2.1.B*).

2.4 Discussion

This study investigated the influence of spatial S-R compatibility on the reproduction of atypical biological kinematics following observational practice. Irrespective of compatibility, post-test performance of the experimental groups was comparable, with *tPHV* occurring early in the movement trajectory, in a manner similar to the observed atypical model. This was supported by the Bayesian statistics that indicated insufficient evidence to accept the experimental hypothesis that the compatible and incompatible groups would differ. The *control group* was not comparable to the experimental groups, with Bayes analysis indicating strong evidence (Jarosz & Wiley, 2014; Raftery, 1995) for the alternative hypothesis (groups being dissimilar) compared to the null hypothesis (groups being similar). Peak velocity occurred towards the midpoint of the movement trajectory, which is similar to the typical model and the pre-existing sensorimotor repertoire, and reflective of the constraints of the task.

The finding from the *compatible group* supports previous work (Hayes et al., 2014) that showed atypical kinematics are represented during observational practice.

As before, the current findings suggest that this occurs within a mechanism that activates sensorimotor processes. However, to control for the influence of spatial S-R compatibility (Hommel & Lippa, 1995), here an *incompatible* stimulus that was rotated through 180 degrees was also presented. The fact that the *incompatible group* reproduced the *atypical* kinematics when physically recalling (from memory) and executing the movement in the opposite left-to-right direction, strengthens the suggestion that sensorimotor adaptation across observational practice occurs via lower-level processes linking visual and motor representations (Catmur & Heyes, 2011; Catmur, Walsh, & Heyes, 2007; R. Cook, Bird, Catmur, Press, & Heyes, 2014). Indeed, there is a possibility participants represented a kinematic landmark during observational practice, such as the position that peak velocity occurs (e.g., spatial position relative to the monitor frame), however this is a less parsimonious explanation that would require a spatial translation through 180 degrees to reproduce an accurate *atypical* trajectory in the left-to-right direction at post-test.

In addition to lower-level sensorimotor processes underlying the adaptation effects, it must be acknowledged that complimentary higher-order processes may have been involved. Specifically, visual attention and intention could have modulated the lower-level processing of the *atypical* kinematics following the explicit instructions given to participants to observe the model with the intention to execute a movement in the post-test that reproduced the same *atypical* movement trajectory (Hayes et al., 2014). Also, having perceived that the *atypical* model had a particular acceleration profile that differed from the *typical* model observed in the pre-test, and/or their own pre-existing sensorimotor repertoire, it follows that across observational practice inductive processes could have adapted and refined the developing sensorimotor representation (Turnham, Braun, & Wolpert, 2011). Indeed, because the *atypical* practice trials were presented in blocked order, sensorimotor

experience and expectation gained from *trial n* would likely influence parameterisation and processing of sensorimotor feedback on *trial n+1* (Tenenbaum, Griffiths, & Kemp, 2006; Turnham et al., 2011).

To conclude, this study confirmed that *atypical* biological kinematics associated with an observed novel action are represented and reproduced following observational practice. Although this effect has previously been shown (Andrew, Bennett, Elliott, & Hayes, 2016; Hayes, Dutoy, et al., 2016; Hayes et al., 2014), the current data and Bayesian analyses extend theoretical knowledge of the processes underlying observational practice by implementing a methodology that controls movement direction of a model during action-observation, and thus spatial compatibility. This method better isolates the representation of *atypica*l kinematics to sensorimotor processes rather than spatial encoding.

3 Chapter Three: Getting off to a shaky start: specificity in autistic planning and feedforward control during sensorimotor learning.

3.1 Introduction

Autism spectrum disorder (henceforth autism) is a neurodevelopmental condition characterised by restricted and repetitive patterns of behaviour, differences in the ability to effectively socially communicate (American Psychiatric Association, 2013), and social cognition (e.g., theory of mind) (Baron-Cohen et al., 1985). Although not part of the formal classification criteria, autistic individuals show clear differences in the functionality of many forms of sensorimotor behaviour (Fournier et al., 2010; Gowen & Hamilton, 2013). For example, they demonstrate greater clumsiness during gait (Calhoun et al., 2011; Rinehart, Tonge, et al., 2006), differences in motor coordination (Green et al., 2002), planning (Glazebrook et al., 2008), postural instability (Teitelbaum, Teitelbaum, Nye, Fryman, & Maurer, 1998) and generally poorer performance on standardised tests of motor function (Green et al., 2009). The sensorimotor basis of these movement differences could be a factor in why autistic individuals experience difficulty executing skilled gestures (praxis) to command (Dewey, Cantell, & Crawford, 2007), developing new actions via imitation learning (Mostofsky et al., 2006), and the acquisition of new sensorimotor skills (e.g., language; learning to throw a basketball) important for interacting within everyday activities.

Most sensorimotor behaviours (e.g., throwing a basketball) are acquired during practice via trial and error learning. During this process, internal action models are developed by representing associations between descending motor commands that drive a limb towards a specified movement goal, the sensory consequences (e.g., reafference from vision and proprioception) of limb movement (Wolpert, Ghahramani, & Jordan, 1995), and external information (e.g., height of a basketball hoop) within the learning environment. Following practice, and learning, internal action models (i.e., inverse model; forward model) form an integral part of a

mechanism that underpins sensorimotor planning, feedforward control, plus the basis for regulating online movement control, and sensorimotor adaptation, by processing and comparing incoming feedback (e.g., vision and proprioception). In autism, the development of action models has been shown to be operational (Gidley Larson et al., 2008; Haswell et al., 2009; Hayes et al., 2018; Izawa et al., 2012; Müller et al., 2004). For example, this was examined in a study where autistic and matched control groups trained on a motor aiming task whilst wearing prisms that perturbed the visuomotor relationship between a performer and the external environment (i.e., target location). At the start of training, both groups were influenced by the prisms such that outcome error was located in the direction of the visual perturbation (Gidley Larson et al., 2008). Importantly, over training both groups demonstrated sensorimotor adaptation by becoming more accurate at achieving the goal of task. Functional adaptation indicated that performers successfully compared expected sensory feedback (e.g., efference copy) of an executed movement on *trial n*, against the actual sensory (reafference; visual and proprioceptive) consequences on *trial n*, and then made corrective adjustments when planning *trial n+1* (Wolpert et al., 2011). Furthermore, when the prisms were removed in a post-test both groups immediately showed after-effects where outcome performance was skewed (i.e., target accuracy decreased) in the opposite direction to the visual perturbation. Taken together, the corrective and adaptation processes, plus the occurrence of after-effects, indicates the sensorimotor processes underpinning action model formation are operational in autism.

Although the formation of action models is operational, there is considerable neuropsychological (Allen, Müller, & Courchesne, 2004; Courchesne, Press, & Yeung-Courchesne, 1993; Müller et al., 2004; Müller et al., 2003; Sharer et al., 2015; Travers, Kana, Klinger, Klein, & Klinger, 2015) and behavioural (Ament et

al., 2015; Fournier et al., 2010; Gowen & Hamilton, 2013; Haswell et al., 2009; Mostofsky, Goldberg, Landa, & Denckla, 2000) evidence indicating that there are processing differences associated with sensorimotor integration during learning, which can influence how movements are subsequently planned and executed. For example, although autistic volunteers developed action models associated with acquiring a novel visuomotor sequence timing task (Hayes et al., 2018), the executed movements were less accurate and more variable than those performed by a control group. Inspection of the movement times indicated the autism group executed significantly slower movements with (acquisition phase), and without (retention test), the availability of knowledge-of-results. Although a detailed kinematic analysis of the movement sequence was not conducted, the elongated movement times are consistent with data from a motor control task where autistic volunteers executed goal-directed aiming movements that were up to 50% longer than controls (Glazebrook et al., 2006). This was associated with significantly greater variability in the spatial position of peak acceleration, which indicates the initial phase of the movement was not as consistent as the movements performed by the control group. This increased variability can be explained by specific difficulties in planning the specification and timing of muscular force into an accurate motor command (i.e., an inverse model, see Wolpert & Kawato, 1998) for a goal-directed movement (Glazebrook et al., 2006; Hughes, 1996; Mari, Castiello, Marks, Marraffa, & Prior, 2003; Rinehart et al., 2001) and/or the efficacy of an associated internal forward model (i.e., efference copy; see Desmurget & Grafton, 2000; Wolpert & Flanagan, 2010) that integrates expected (motor outflow; efference) and actual (sensory inflow; reafference) sensorimotor (i.e., vision; proprioception) information (Glazebrook et al., 2006; Mosconi et al., 2015; Schmitz et al., 2003). It is important to note that although the autism group showed these specific differences, they were comparable

in terms of movement topology, as well as processing and integrating visual information for online movement control (i.e., no significant difference in the variability associated with the spatial position of peak velocity).

In the present study, sensorimotor learning in autism was quantified by analysing accuracy and variability of visuomotor sequence timing (i.e., total time and relative time), plus the contribution of sensorimotor planning, feedforward control and online visuomotor control. Autistic and control participants practised a novel 3-segment visuomotor sequence timing task (VSTT) during an acquisition phase with terminal knowledge-of-results. To examine sensorimotor learning, the VSTT was performed in a retention phase without knowledge-of-results. Based on previous work (Hayes et al., 2018) that used the same VSTT, it was expected that autistic learners would acquire the novel VSTT by reducing accuracy and variability of timing error as a function of trial-and-error learning, and the processing of knowledge-of-results. Although the autism group is expected to acquire the VSTT, it is expected that their sensorimotor performance will be less accurate and more variable than a matched-control group during acquisition and retention. To understand how the processes underlying the acquisition of relative timing in autism operate in an unconstrained learning environment, learners were allowed to adopt a self-selected, rather than an experimenter-imposed, relative timing pattern (Heuer & Schmidt, 1988; Schmidt, 1985). Based on the data from a related manual aiming motor control task (Glazebrook et al., 2006), both groups were expected to execute the VSTT with comparable sequence timing structures. Finally, if the expected differences in timing accuracy (i.e., longer movement times) and variability are associated with the specificity of the underlying autistic sensorimotor planning, and feedforward control processes the autism group were expected to show greater variability in the spatial position of peak acceleration compared to the matched-

control group. However, given that visual online control appears to be operational in some visuomotor tasks (Glazebrook et al., 2006; Mosconi et al., 2015), it is expected there will be no difference between the two groups in variability in the spatial position of peak velocity.

3.2 Method

Participants

The volunteers were recruited from an autistic society in North West England and the host University. Volunteers were provided with a participant information sheet to read, followed by an opportunity to ask questions to clarify the experimental procedures, and then a time period to consider whether they would like to consent to engage in the study. Following this process, 26 control (25 male; 1 female), and 26 autistic (25 male; 1 female) volunteers participated in the study. All participants were screened via self-report for the following exclusion criteria: dyspraxia, dyslexia, epilepsy and other neurological or psychiatric conditions. The autistic participants 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 autistic participants met the threshold for autism spectrum disorder on the ADOS-2 total classification score, and on the communication, and social interaction subscales. Groups were equated for age, as well as full-scale verbal, and performance, IQ as measured via the Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999). Participant characteristics are presented in *Table 3.1*. The experiment was designed in accordance with the 1964 declaration of Helsinki and received full approval by the host University research ethics committee.

Table 3.1: Characteristics of autism and control participants.

	Autism (n = 26)		Control (n = 26)		t test p value
	Mean (SD)	Range	Mean (SD)	Range	
Chronological age in years	25 (7)	18-44	25 (7)	18-45	p = 0.845
Full scale IQ	107 (9)	91-125	109 (8)	94-123	p = 0.396
Verbal IQ	106 (11)	88-130	109 (8)	96-125	p = 0.214
Performance IQ	106 (11)	82-128	107 (12)	82-128	p = 0.891
Gender	25M : 1F		25M : 1F		

Apparatus

Participants sat at a table in front of a 21-inch CRT monitor (Iiyama Vision Master 505) located at a viewing distance of approximately 900 mm. The CRT monitor had a resolution of 1280 x 1024 pixels, and a refresh rate of 85 Hz. The monitor was connected to a desktop PC (Dell Optiplex GX280), which received input from a hand-held stylus as it moved on a graphics tablet (Wacom Intuos Pro XL) (*see Figure 3.1*). Experimental stimuli were presented on the CRT monitor 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

Prior to the main study, all participants performed a familiarisation period where they sat in front of the CRT monitor (*Figure 3.1*) and received a visual demonstration, plus verbal instructions, of the VSTT. Three (start, middle, and end)

red target circles (diameter = 12.50 mm) were displayed across the centre of the CRT monitor with an equidistant horizontal extent of 18.75 mm. A white cursor (diameter = 6.25 mm) was also drawn on the CRT monitor and represented the human motion produced as a participant moved the hand-held stylus on the graphics tablet. Participants were informed that to start the 3-segment VSTT they should move the white cursor so that it was positioned in the left-hand start target. Once achieved, the three targets turned green to signal that participants were to begin executing the VSTT. The VSTT required the cursor to be moved horizontally rightwards so that it was located in the middle target (segment 1), followed by a leftwards reversal to locate the cursor in start circle (segment 2), and finally a rightwards reversal to move the cursor through the middle target and then stop in the right-hand end target (segment 3). Once participants confirmed they understood how to complete the VSTT, they were next informed the goal of the task was to do this with a criterion timing goal of 1700ms. All participants were informed, and subsequently confirmed they understood the unit of milliseconds in relation to the more typical unit of seconds. The acquisition period then commenced, with participants performing thirty-six trials of the VSTT using the preferred arm. To ensure participants performed the correct spatial dimensions of the movement sequence, the stimulus generation routine was able to present an error message on the monitor if the cursor did not pass through each target in the correct order (NB. no error trials were recorded). To facilitate sensorimotor performance and adaptation in the acquisition phase, terminal feedback in the form of knowledge-of-results was presented on the monitor following each trial (e.g., Too Fast or Too Slow by 350 ms). All participants were informed and subsequently confirmed that they understood how knowledge-of-results after trial *N* could be used to modify trial *N* +

1. Following the acquisition period, six retention trials without knowledge-of-results were completed to assess sensorimotor learning.

Data Reduction

Using a custom written MATLAB routine the start and end of each 3-segment movement sequence was identified from the x-axis position data. The start was defined as the moment the centre of the cursor moved beyond the perimeter of the start-target, and the end equated to when the centre of the cursor moved within

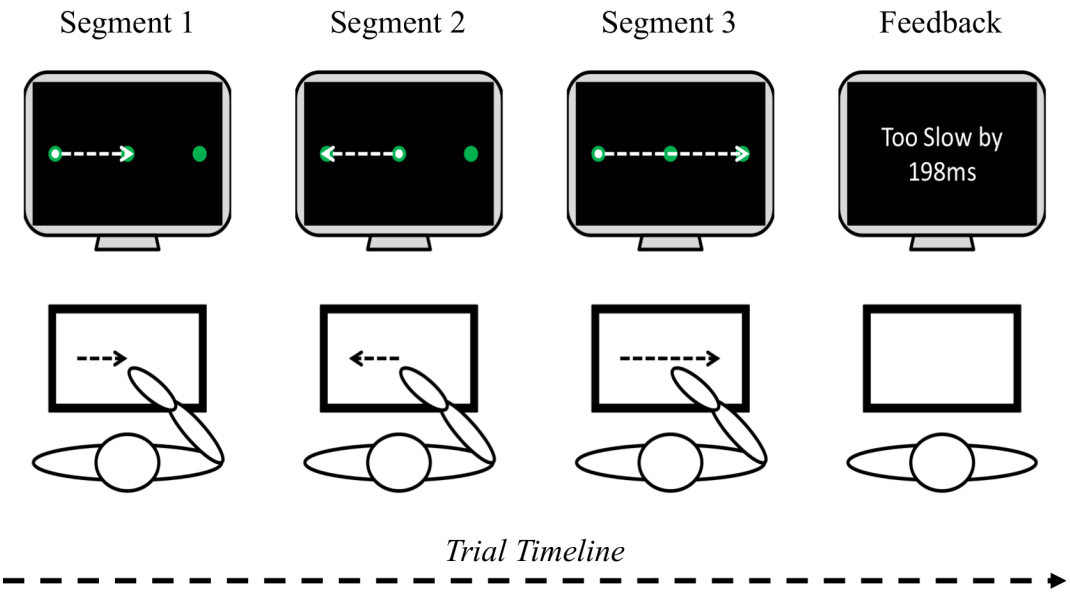

Figure 3.1: A schematic representation of the visuomotor sequence timing task that has a timing goal of 1700 ms. The sequence was presented as three red targets (diameter = 12 mm) and is depicted by the arrows in Segment 1 (start target to centre target), Segment 2 (centre target to start target), and Segment 3 (start target to end target). The target positions had an equidistant extent of 100 mm between the centre of each target. The white circle depicts the cursor (diameter = 6 mm) and represents the motion of the hand-held stylus drawn on the monitor. Feedback on the CRT monitor represents knowledge-of-results provided to the participant in ms.

the perimeter of the end-target. The time-series position data for each acquisition and retention test trial was then extracted for all participants. The position data for each trial were processed using a low-pass 4th order autoregressive filter with an 8 Hz cut-off, and then differentiated using a 3-point central difference algorithm to obtain

velocity and acceleration. For each trial, the end of the movement made in segment 1 and 2 was identified by searching for a zero-crossing in the velocity data that was associated with a change in movement direction (i.e., reversal).

Having identified the start and end of a trial, as well the individual segments within the sequence, five dependent variables were extracted: *temporal constant error, temporal variable error*, *relative timing*, *spatial variability at the position of peak acceleration (sdPA)* and *spatial variability at the position of peak velocity (sdPV)*. *Temporal constant error* is a measure reflecting the average signed deviation (e.g., plus or minus) between a participant's movement time on *trial n* (e.g., 1900 ms) and the criterion timing goal that is 1700ms (e.g., a movement time of 1900 ms would lead to +200 ms, and a movement time of 1500 ms would lead to -200 ms). *Temporal variable error* reflects the variability in the participant's responses across a set number of trials (e.g., 6 trials, see the data analysis section below) around the average CE for the same 6 trials. To quantify *relative timing* (i.e., a measure of how the 3 segments are proportionally expressed relative to the total movement time; Schmidt, 1975), each segment (i.e., segment 1) within the 3-segment sequence was expressed as a percentage of the overall movement time. For example, if on *trial n* a participant performs the VSTT in a total movement time of 1800 ms, and the segment movement times are 300, 500 and 1000 ms respectively, the *relative timing* structure would be 17%, 28%, 56%. To quantify measures associated with underlying sensorimotor control, *spatial variability at the position of peak acceleration*, and *peak velocity,* was extracted across trials. The variability in distance travelled at *peak acceleration* is reflective of the effectiveness of planning the correct specification of muscular forces, combined with early sensorimotor corrections based on the comparison of expected to actual efference (see Elliott et al., 2010).

Data Analysis

To examine changes in motor performance across acquisition, intra-participant mean *temporal constant error* and *temporal variable error* was calculated from the first and last six of the 30 acquisition trials. These data were submitted to a 2 Group (autism; control) x 2 Phase (early; late) mixed design ANOVA. To quantify performance of the three individual movement segments, intra-participant mean *relative timing*, *sdPA*, and *sdPV* were calculated from the first and last six trials of acquisition. For *relative timing*, intra-participant means for each segment were submitted to separate 2 Group (autism; control) x 2 Phase (early; late) mixed design ANOVAs. Intra-participant means for *sdPA* and *sdPV* were submitted to separate 2 Group (autism; control) x 2 Phase (early; late) x 3 Segment (one; two; three) mixed design ANOVAs.

To assess sensorimotor learning in the retention test, intra-participant mean *temporal constant error* and *temporal variable error* was calculated for the six retention trials and submitted to a 2 Group (autism; control) one-way ANOVA. Similarly, intra-participant mean *relative timing* from each segment was calculated for the six retention trials and submitted to separate 2 Group (autism; control) one-way ANOVAs. For *sdPA* and *sdPV,* intra-participant means from the six retention trials were submitted to separate 2 Group (autism; control) x 3 Segment (1, 2, 3) mixed design ANOVAs.

To establish whether the feedback provided following each trial accounted for changes in total movement time throughout acquisition the knowledge-of-results provided following each was trial was first calculated by subtracting the participants movement time on *trial n* from the target movement time (1700 ms). Thus providing the expected direction and magnitude of any correction that should occur on *trial*

n+1. Secondly the actual correction made by a participant on *trial n+1* was calculated by subtracting the participants movement time on *trial n* from their *trial n+1* performance. The correlation between knowledge-of-results and the actual correct was then computed for each participants' trials during the early and late phases of acquisition. High negative correlation would indicate that the participants were using the feedback provided to adapt their motor performance {Blandin, 2000 #691}. All correlation scores were then submitted to a 2 Group (autism; control) x 2 Phase (early; late) mixed design ANOVA following Fisher's R to Z transformation.

Significant main and/or interaction effects were decomposed using Fisher LSD post-hoc procedure, with alpha was set at $p < 0.05$. Partial eta squared (η_p^2) was used to express the size of each effect. ANOVAs that included three levels of segment as a within-subject factor were checked for violation of sphericity using Mauchly's Sphericity Test, and corrected where necessary with Greenhouse-Geisser (i.e., $p < 0.05$).

3.3 Results

Acquisition

Group mean *temporal constant error* is illustrated in *Figure 3.2.A*, and movement time data in *Table 3.2*. ANOVA revealed a non significant group x phase interaction [F (1, 50) = 3.51, $p > 0.05$, $\eta_p^2 = 0.066$], but significant main effects for group [F (1, 50) = 8.75, $p < 0.01$, $\eta_p^2 = 0.149$] and phase [F (1, 50) = 92.21$p < 0.001$, $\eta_p^2 = 0.648$]. Although the autism group differed on average by 298 ms compared to the control group, the autism group demonstrated a %Δ 64, and the control group a %Δ 65, in *temporal constant error* from early acquisition (Autism: 1234.83 ± 667.10

ms; Control: 808.54 ± 384.82 ms) to late acquisition (Autism: 449.07 ± 348.65 ms; Control: 279.49 ± 237.43 ms).

Table 3.2: Mean (SD) Movement Time (ms) Data Presented as a Function of Group and Phase.

		Early Mean (SD)	Late Mean (SD)	Retention Mean (SD)
Autism	Segment 1	775 (155)	650 (108)	671 (128)
	Segment 2	887 (210)	620 (107)	665 (105)
	Segment 3	1273 (364)	875 (182)	958 (250)
	Total	2935 (667)	2145 (349)	2294 (438)
Control	Segment 1	707 (101)	598 (76)	606 (70)
	Segment 2	784 (159)	588 (58)	591 (59)
	Segment 3	1018 (195)	794 (143)	794 (122)
	Total	2509 (385)	1980 (237)	1991 (206)

Group mean *temporal variable error* is illustrated in *Figure 3.2.B*. ANOVA revealed a non significant group x phase interaction [F (1, 50) = 0.80, $p > 0.05$, η_p^2 = 0.016], but a significant main effect for phase [F (1, 50) = 49.71, $p < 0.001$, η_p^2 = 0.499]. There was no significant main effect for group [F (1, 50) = 0.69 $p > 0.05$, η_p^2 = 0.013]. The autism group demonstrated a %Δ 54, and the control group a %Δ 70, in *temporal variable error* from early acquisition (Autism: 498.29 ± 279.58 ms; Control: 497.32 ± 350.22 ms) to late acquisition (Autism: 229.79 ± 108.10 ms; Control: 150.82 ± 97.69 ms).

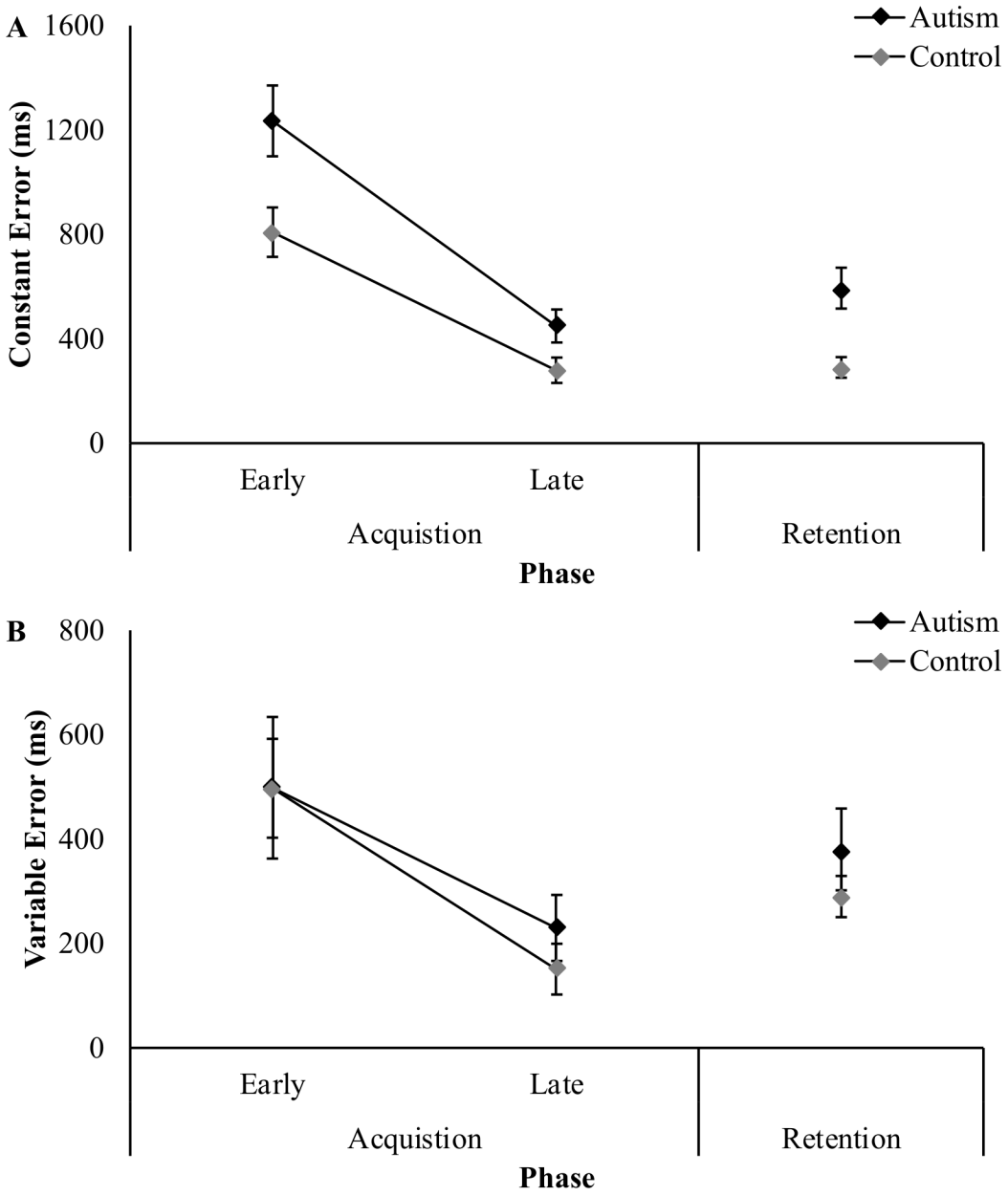

Figure 3.2: Mean temporal constant error (A) and mean temporal variable error (B) presented as a function of group and phase. Error bars represent standard error of the mean.

Group mean *relative timing* data for segments 1, 2 and 3 is illustrated in *Figure 3.3*. For segment 1, ANOVA revealed no significant main effect of group [F (1, 50) = 1.32, $p > 0.05$, $\eta_p^2 = 0.026$], but a significant effect of phase [F (1, 50) = 47.96, $p < 0.001$, $\eta_p^2 = 0.490$] and a group x phase interaction [F (1, 50) = 5.03, $p < 0.05$, $\eta_p^2 = 0.091$]. Post hoc analysis of the interaction indicated that although both

groups significantly (*ps* < 0.001) increased *relative timing* in segment 1 from the early to late phase of acquisition, the autism group demonstrated a greater increase (14%) than the control group (7%). For segment 2, ANOVA revealed no main effect of group [F (1, 50) = 1.99, $p > 0.05$, $\eta_p^2 = 0.038$], or a group x phase interaction [F (1, 50) = 0.01, $p > 0.05$, $\eta_p^2 = 0.001$. There was a significant main effect of phase [F (1, 50) = 12.23, $p < 0.01$, $\eta_p^2 = 0.197$] in segment 2, with *relative timing* being reduced by 5% from the early to late phase of acquisition. For segment 3, ANOVA revealed no group x phase interaction [F (1, 50) = 2.57, $p > 0.05$, $\eta_p^2 = 0.049$], but there were significant main effects of phase [F (1, 50) = 2.57, $p < 0.05$, $\eta_p^2 = 0.077$] and group [F (1, 50) = 6.09, $p < 0.05$, $\eta_p^2 = 0.109$]. Although both groups exhibited a significant reduction in *relative timing* in segment 3 from the early to late phase of acquisition ($p < 0.05$), the autism group (42 ± 4 %) spent proportionally longer ($p < 0.05$) in this segment than the control group (40 ± 3 %).

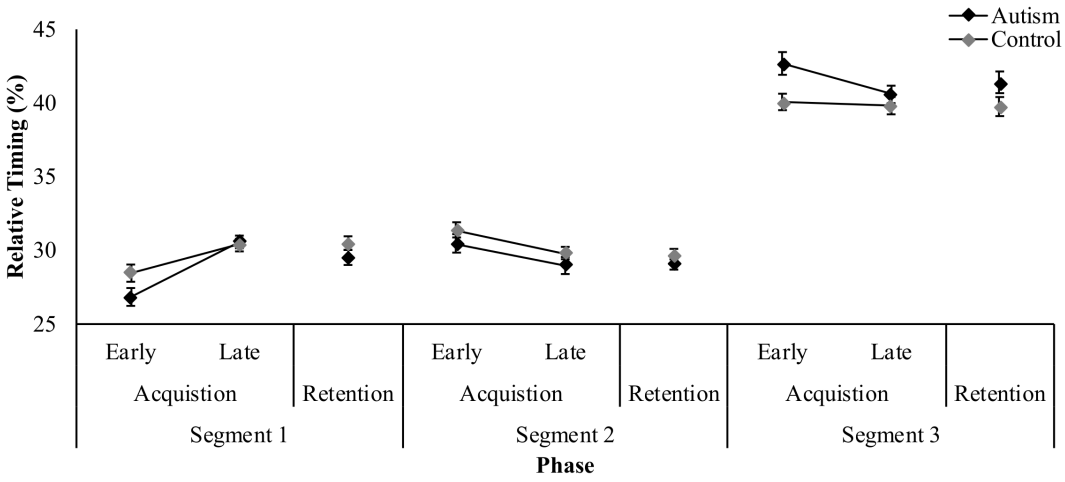

Figure 3.3: Mean relative timing as a function of group, segment and phase. Error bars represent standard error of the mean.

Group mean *sdPA* is illustrated in *Figure 3.4.A*. ANOVA revealed significant main effects of group [F (1, 50) = 4.792, $p < 0.05$, $\eta_p^2 = 0.087$], segment [F (1.47,

73.36) = 121.29, $p < 0.001$, $\eta_p^2 = 0.708$], and phase [F (1, 50) = 20.91, $p < 0.001$, $\eta_p^2 = 0.295$], plus a significant segment x phase interaction [F (1.40, 69.95) = 20.04, $p < 0.001$, $\eta_p^2 = 0.286$]. Overall, *sdPA* was greater in the autism group (10.27± 8.78 mm) compared to control group (8.78± 6.40 mm). Also, *sdPA* was significantly (*ps < 0.05*) greater in segment 2 (17.19 ± 6.21 mm) and segment 3 (6.20 ± 2.62 mm) than segment 1 (5.19 ± 3.36 mm). Finally, post hoc analysis of the interaction indicated that *sdPA* decreased significantly by 7.79 mm ($p < 0.001$) from early to late acquisition in segment 2, whereas there was no significant change in segment 1 or 3 (*ps* < 0.05).

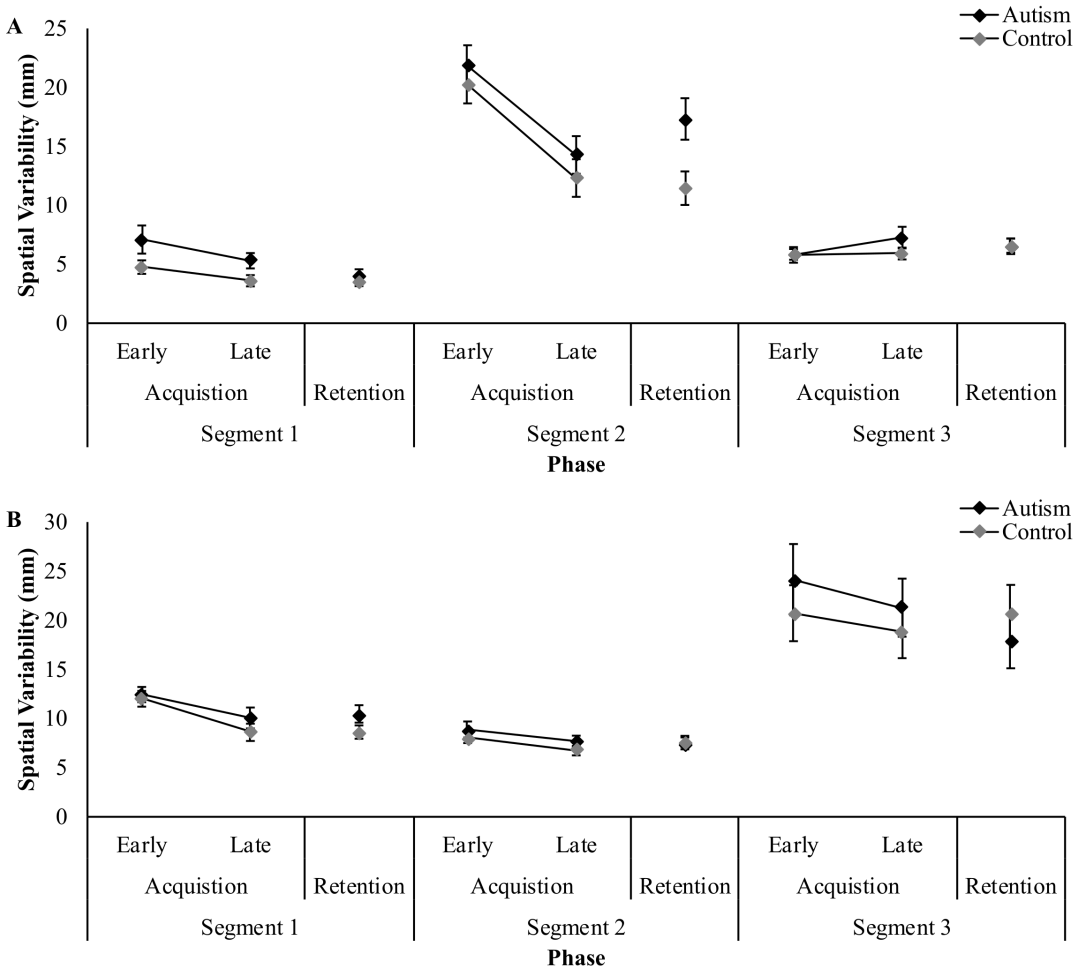

Figure 3.4:Mean spatial variability at peak acceleration (A) and mean spatial variability at peak velocity (B) as a function of group, segment and phase. Error bars represent standard error of the mean.

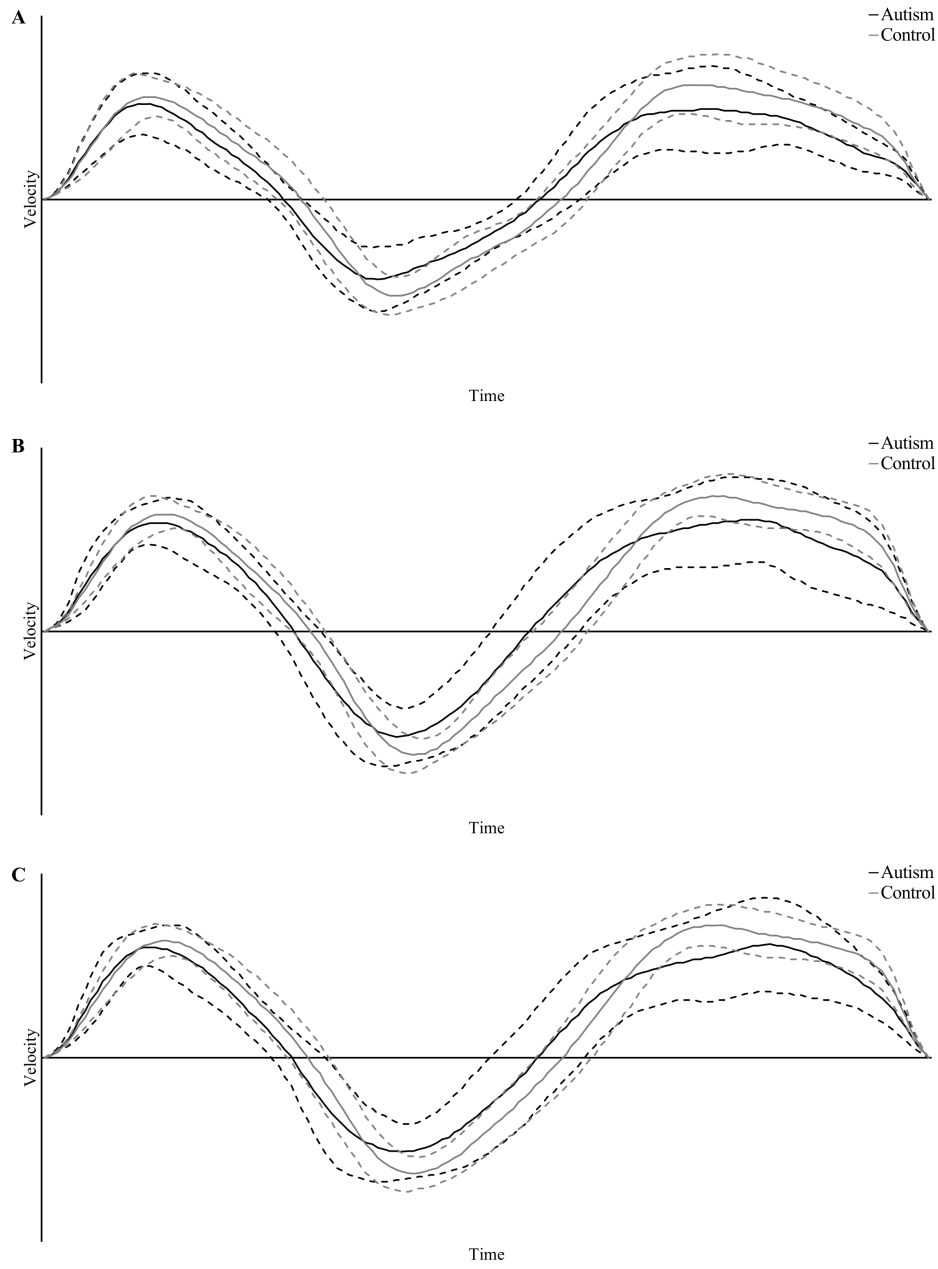

Figure 3.5: Mean topographical velocity traces for the autism (black trace) and control (grey traces) for early (A), late (B), and retention (C). Dashed traces indicate standard deviation of the mean.

Group mean *sdPV* is illustrated in *Figure 3.4.B*. ANOVA revealed no significant main effect of group [F (1, 50) = 1.587, $p > 0.05$, $\eta_p^2 = 0.031$], and no significant 2-way or 3-way interactions (*ps > 0.05*). However, there was a significant main effect of phase [F (1, 50) = 4.23, $p < 0.05$, $\eta_p^2 = 0.078$] and segment [F (1.15,

57.31) = 51.43, $p < 0.001$, $\eta_p^2 = 0.507$. *sdPV* decreased by 2.19 mm from the early to late phase of acquisition. Also, while *sdPV* was greater in segment 1 (10.77 ± 2.99 mm) compared to segment 2 (7.84 ± 2.17 mm) ($p < 0.001$), it was even greater still in segment 3 (21.23 ± 12.18 mm) ($p < 0.001$).

Retention

ANOVA on *temporal constant error* revealed a significant main effect of group [F (1, 50) = 10.24, $p < 0.01$, $\eta_p^2 = 0.170$], whereby the control group had a *temporal constant error* score that was 304 ms lower than the autism group when performing the timing goal in the retention test when knowledge-of-results was removed.

ANOVA on *temporal variable error* revealed a significant main effect of group [F (1, 50) = 11.83, $p < 0.01$, $\eta_p^2 = 0.191$], whereby the control group had a *temporal variable error* score that was 90 ms lower than the autism group when performing the timing goal in the retention test when knowledge-of-results was removed.

ANOVA on *relative timing* data revealed no significant main effects of group for segment 1 [F (1, 50) = 12.43, $p > 0.05$, $\eta_p^2 = 0.039$], segment 2 [F (1, 50) = 0.79, $p > 0.05$, $\eta_p^2 = 0.016$], or segment 3 [F (1, 50) = 2.83, $p > 0.05$, $\eta_p^2 = 0.054$]. As illustrated in *Figure 3.3*, the autism group (Segment 1: 30 ± 3 %; Segment 2: 29 ± 3 %; Segment 3: 41 ± 4 %) executed the three-segment movement sequence with a similar *relative timing* as the control group (Segment 1: 30 ± 2 %; Segment 2: 30 ± 2 %; Segment 3: 40 ± 3 %) in retention.

ANOVA on *sdPA* revealed significant main effects for segment [F (1.31, 65.54) = 58.83, $p < 0.001$, $\eta_p^2 = 0.541$] and group [F (1, 50) = 6.06, $p < 0.05$, $\eta_p^2 =$

0.108], plus a significant group x segment interaction [F (2, 100) = 5.23, $p < 0.01$, η_p^2 = 0.095]. As illustrated in *Figure 3.4.A*, *sdPA* was greater (both *ps* < 0.001) in segment 2 (14.39 ± 8.6 mm) compared to segment 1 (3.85 ± 2.22 mm) and 3 (6.55 ± 3.19 mm). The greatest difference in *sdPA* between the autism and control groups occurred in segment 2 only ($p < 0.001$; Autism: 17.32 ± 8.97 mm; Control: 11.45 ± 7.25 mm).

ANOVA on *sdPV* revealed a significant main effect of segment [F (1.19, 59.27) = 28.65 $p < 0.001$, η_p^2 = 0.364]. *sdPV* was greater in segment 1 (9.55 ± 4.10 mm) compared to segment 2 (7.57 ± 2.96 mm) ($p < 0.01$], and even greater still in segment 3 (19.27 ± 14.56 mm) (*ps* < 0.001). Unlike *sdPA,* there was no significant main effect of group [F (1, 50) = 0.54, $p > 0.05$, η_p^2 = 0.001] or group x segment interaction [F (2, 100) = 0.97, $p > 0.05$, η_p^2 = 0.019]. *sdPV* did not differ between the autism and control groups across the 3 segments.

Relationship between knowledge-of-results and changes in motor performance during acquisition.

ANOVA revealed no significant main effect of phase [F (1, 50) = 3.66 $p >$ 0.05, η_p^2 = 0.068], or group [F (1, 50) = 0.51 $p > 0.05$, η_p^2 = 0.010]. There was also no phase x group interaction [F (1, 50) = 0.06 $p > 0.05$, η_p^2 = 0.001], suggesting that both groups similarly used knowledge-of-results to adapt their motor output during acquisition. As shown in *Table 3.3* high negative correlations were present for both groups in all phases of acquisition suggesting that the feedback being provided was driving changes in motor performance.

Table 3.3: Mean correlations between knowledge-of-results and changes in motor performance during acquisition.

	Early Mean (SD)	Late Mean (SD)
Autism	-0.77 (0.19)	-0.74 (0.15)
Control	-0.80 (0.14)	-0.74 (0.17)

3.4 Discussion

The current study quantified sensorimotor learning in autism when acquiring a novel VSTT. As predicted, the autism and control groups became significantly more accurate and consistent at executing the VSTT across the acquisition phase as a function of trial-and-error learning in the presence of knowledge of results. Although both groups showed comparable magnitudes (autism group = 64 %Δ; control group = 65 %Δ) of sensorimotor adaptation during acquisition, the significant group effect for *temporal constant error* indicated the autism group executed longer movement times (see Table 2) in the acquisition phase (slower by 298 ms) and retention test (slower by 304 ms). Similarly, although both groups also showed comparable magnitudes of change (autism group = 54 %Δ; control group = 70 %Δ) for *temporal variable error* during acquisition, the autism group were significantly more variable in retention (Autism: 380.21 ± 107.35 ms; Control: 289.91 ± 79.98 ms). These accuracy and consistency effects replicated previous work (Hayes et al., 2018) that also examined sensorimotor learning in autism using exactly the same VSTT, and in addition, confirmed the expectation that the underlying sensorimotor learning and control processes in autism show specificity effects that constrain the nature of overt motor behaviour.

To examine these specificity effects, the visuomotor sequence timing structures (*relative timing*) were quantified in a task where participants used a self-selected rather than experimenter-imposed relative timing pattern (Heuer & Schmidt, 1988; Schmidt, 1985). The analysis revealed that both groups made comparable significant directional (e.g., increase in segment 1; and decreases in segment 2 and 3) adaptations to the proportion of time spent executing the 3 individual segments within the VSTT. These changes led to both groups executing comparable movements, and indicated that the sensorimotor processes underlying the emergence of self-selected (preferred) (Heuer & Schmidt, 1988) relative timing structures in autism is operational and comparable to a matched-control group. Although the *relative timing* data showed adaptation effects across all segments, the group difference in segment 3 showed the autism group spent proportionally more time in the final segment than the control group. This additional time is likely to be related to a combination of factors that influence visuomotor control in autism. For example, the elongated segment movement time might be a strategic aiming process that autistic learners adopted in order to accommodate a nosier autistic sensorimotor system (Glazebrook et al., 2006) and/or ineffective movement planning (Rinehart, Bellgrove, et al., 2006). Therefore, an effective strategy is to spend more time in the final segment utilising the availability of vision to home in on the final target to terminate the movement accurately (Elliott et al., 2010; Saunders & Knill, 2005), and then to use the information extracted during visual processing for offline motor planning for the next trial (Khan, Elliott, Coull, Chua, & Lyons, 2002). It is important to note that although the autism group on average spent a greater percentage of time in segment 3, they demonstrated adaptation across the acquisition phase leading to a shorter movement time. Whilst the adaptation process is a positive finding and indicates that training may modulate sensorimotor function in autism,

the requirement to adapt is most likely due to sensorimotor integration being less effective, or different, in autism compared to the processes operating in matched-controls (Haswell et al., 2009; Izawa et al., 2012; Mosconi et al., 2015). Therefore, the increased movement time likely reflects the additional processing time needed to effectively integrate (sensory) visual feedback with the ongoing manual aiming movement (Glazebrook et al., 2009).

The examination of kinematic markers *sdPA* and *sdPV* indicated that the autism group demonstrated greater spatial variability at *sdPA*, but comparable spatial variability at *sdPV*. These two kinematic markers suggest that the differences observed in timing accuracy, variability and relative timing during sensorimotor learning in autism are in part related to the efficacy of the underlying sensorimotor processes associated with planning, and feedforward control (i.e., > *sdPA*), rather than visual online control (i.e., ≈ *sdPV*). During goal-directed aiming, as per the VSTT, an initial sensorimotor motor plan is formed from an inverse model (Wolpert & Kawato, 1998) that receives input state estimation (i.e., multisensory information processing) and previous experience (e.g., *priors* from past learning). Once generated, the sensorimotor plan is used to form a motor command, and an efference copy (Von Holst, 1954) that functions as a forward model (i.e., containing expected sensory consequence) for sensorimotor control (Desmurget & Grafton, 2000; Wolpert et al., 1995; Wolpert & Kawato, 1998). In the present study, *sdPA* is a measure of variability in spatial position of peak acceleration in the limb following movement initiation, and therefore reflects processing activity associated with feedforward control during motor execution (Elliott et al., 2010). During this early stage, expected sensory consequences, and actual sensory consequences (Desmurget & Grafton, 2000), are compared with any discrepancy forming the basis of sensorimotor adjustments. Data recorded during tactile sensory perception

(Blakemore et al., 2006) indicated that autism and control groups showed comparable attenuation of the tickliness of self-produced touch relative to external touch, which indicates the feedforward predictive mechanism that compares expected and an actual sensory consequences is functional in autism. Therefore, the greater *sdPA* in the autism group is most likely related to ineffective sensorimotor planning based on an inverse model and state estimation. This suggestion is consistent with data from manual aiming (Glazebrook et al., 2006) and force production (Mosconi et al., 2015; Schmitz et al., 2003) tasks that show feedforward differences in autism are related to the efficacy of the sensorimotor planning processes that control the specification of muscular forces, and the control of force output. Although the acquisition period was only thirty trials, the *sdPA* revealed that variability reduced on average from the early and late phases, with a greater reduction in segment 2. This adaptation effect provides evidence that the feedforward function of an internal action model formed during practice can be refined during sensorimotor learning.

As stated, the difference between the autism and control groups was not evident in the *sdPV* data. The modulation of sensorimotor variability at the point of peak velocity is indicative of functional sensorimotor control based on reducing the difference between the perceived sensory consequences (i.e., visual and proprioceptive reafference) relating to the executed action, and the expected motor and sensory consequences specified in forward models (Elliott et al., 2010). Therefore, although there are elements of feedforward control that differ in autism (Mosconi et al., 2015; Schmitz et al., 2003; Wang et al., 2015), the feedback-based control processes that continually operate as the movement trajectory unfolds (Saunders & Knill, 2005) are functional. Furthermore, and consistent with the *sdPA* data, the significant reduction in variability from early to late phase following

practice indicates that the feedback-based processing mechanism changes functionality and is refined via sensorimotor learning. This sort of adaptation might be engaged to modulate the planning issues related to the specification of muscular forces in autism. Although not developed via sensorimotor learning, a similar compensation strategy was reported during manual load-lifting (Schmitz et al., 2003) where autistic participants increased loading durations to facilitate feedback-based control processes in order to overcome issues related to differences in feedforward control.

In summary, the current study found evidence of intact sensorimotor motor learning of a novel VSTT in autism. Although learning occurred across trial-and-error practice, the autism group performed longer movement times that led to less accurate and more variable movements. Kinematic analysis of the autistic movement trajectories indicated ineffective feedforward control processes associated with the planning the specification of forces, but operational feedback-based sensorimotor control. The fact the feedforward and feedback-based control processes were refined across practice offers an indication that these processes are susceptible to training. Understanding the operation of feedforward and feedback-based control processes during sensorimotor learning provides an opportunity to explore how similar control processes influence social-motor actions in autism.

4 Chapter Four: Facilitating sensorimotor integration via predictable practice underpins the imitation of atypical biological kinematics in autism spectrum disorders.

4.1 Introduction

Learning novel actions through voluntary imitation is a fundamental part of human development, and is facilitated by intentional, attentional and sensorimotor processes (Heyes, 2001). During voluntary imitation (henceforth imitation), an individual observes a model that typically prescribes a higher-order action-goal (e.g., to use chop sticks), as well as the lower-level kinematic properties (e.g., velocity of the digits) constraining the means of achieving the action-goal. In the action-observation phase of imitation, the action-goal and lower-level kinematics are encoded within a sensorimotor system directly linking perception to action (Prinz, 1997). After observation, processes associated with sensorimotor planning are engaged to control the specification of forces required for initial execution of the to-be-imitated movement pattern. During, and after, movement execution, efferent and afferent sensorimotor information is integrated and processed (by feedforward and feedback control mechanisms) to support encoding. Over repeated imitation trials, an action-representation is developed and refined so that an imitated movement becomes similar to the observed biological motion characteristics displayed by the model. While the process of imitation is learned and operational across typical development (Legare & Nielsen, 2015; Oostenbroek et al., 2016), it has been claimed that autistic individuals show a specific difficulty imitating the lower-level biological kinematic properties of an observed action (DeMyer et al., 1972; Hayes, Andrew, et al., 2016; Hobson & Lee, 1999; Rogers et al., 1996; Stewart et al., 2013; Wild et al., 2012).

A previous examination of the imitation of biological kinematics in autism (Hayes, Andrew, et al., 2016), displayed two models with the same movement amplitude and time, but different underlying kinematics which were presented in a randomised order. The first, a control model displayed typical kinematics that had a

bell-shaped velocity profile (peak velocity occurred at ~50% of the movement trajectory), which could be imitated by rescaling a typical movement profile from an existing motor repertoire (Carmo, Rumiati, Siugzdaite, & Brambilla, 2013; Rumiati et al., 2005). As predicted, they showed no difference between autism and control groups when imitating the control model. The second, an experimental model displayed atypical kinematics where peak velocity occurred at 18% of the movement trajectory. This model ensured participants needed to represent the atypical kinematics during action-observation in order to reorganise the sensorimotor system to plan and execute a motor response that was similar to the observed kinematics. Unlike the control group that successfully imitated the atypical biological kinematics (Hayes, Andrew, et al., 2016), the autism group produced a movement characterised by a typical kinematic profile. However, the autism group did become significantly more accurate and consistent at imitating the movement time goal across the imitation training period. Together, these findings indicate that although certain processes underlying voluntary imitation are functional, there is a specific difficulty imitating atypical biological kinematics that is likely to be related to how the sensorimotor processes are engaged across consecutive imitation trials.

Further insight into the operation of sensorimotor processes in autism is evident from automatic imitation studies (Bird et al., 2007; Edey et al., 2016; Hamilton et al., 2007; Press et al., 2010; Schulte-Rüther et al., 2017; Sowden et al., 2016; Spengler et al., 2010) in which autistic adults have been shown to generate sensorimotor response times similar to matched-controls when observing task irrelevant biological action stimulus (e.g., a human hand lifting an index fingers). In other words, movement observation had a direct automatic influence on motor execution (Brass et al., 2001), thereby confirming the sensorimotor processes responsible for processing biological motion during action-observation are

operational in autism (Nackaerts et al., 2012; Saygin et al., 2010). Therefore, the implication for voluntary imitation is that the difficulty imitating atypical biological kinematics is not solely associated with a specific imitation mechanism that directly represents and encodes biological motion during the action-observation phase (Bernier et al., 2007; Williams, Whiten, & Singh, 2004; Williams et al., 2001). Rather, there may be differences in other complimentary general sensorimotor processes (Hamilton, 2013; Leighton, Bird, Charman, & Heyes, 2008) that are engaged to represent and refine the observed biological kinematics during imitation. For example, by presenting typical and atypical biological kinematic models in a randomised trial order (Hayes, Andrew, et al., 2016), sensorimotor information from trial *n* (e.g., atypical model) would often be different to trial *n+1* (e.g., typical model), thus impacting upon the refinement of a sensorimotor representation through the comparison of expected (efference) and actual (reafferent) sensorimotor consequences (Elliott et al., 2001; Wolpert et al., 2011). In addition, there would be an increased trial-to-trial requirement to plan and specify the force requirements to imitate velocity profiles with different magnitudes, one of which (i.e., that characterised by atypical kinematics) did not already exist within the sensorimotor repertoire.

To better understand the sensorimotor planning and integration processes in voluntary information in autism, examined imitation learning (pre-test, acquisition-phase, and post-test) of a novel motor behaviour using a protocol designed to facilitate the encoding of *atypical* biological kinematics. Rather than using a randomised trial order (Hayes, Andrew, et al., 2016), the acquisition-phase was arranged with a fixed trial order, where the same *atypical* model was presented consecutively across all learning trials. The fixed trial order is expected to facilitate imitation learning by optimising (Kantak & Winstein, 2012) the comparison and

processing of expected (efference copy - feedforward control) and actual (reafference - feedback control) sensorimotor consequences from trial *n* to trial *n+1* (Elliott et al., 2001; Wolpert et al., 2011). Therefore, over repeated trials, an internal action model can be refined and encoded so that the observer's movement becomes similar to the *atypical* biological kinematics displayed by the model.

Based on the above synthesis, five sets of *a priori* hypotheses were specified to test separate aspects of imitation via orthogonal planned comparisons. The first set of planned comparisons tested the hypothesis that autistic individuals will generally be less effective at voluntary imitation than matched control individuals. The second and third sets of planned comparisons examined whether imitating in a fixed trial order underpins sensorimotor adaptation in autism by facilitating the integration and encoding of *atypical* biological kinematics. Specifically, this compared imitation of the *atypical* model in the pre-test (randomised trial order) against the middle-acquisition block, as well as the early-acquisition block against the average of the middle and late-acquisition blocks. In both cases, if the fixed trial order facilitates sensorimotor adaptation in autism it would be expected that imitation will be significantly more accurate compared to when the trial order was random (pre-test), and when more learning trials had been completed across the fixed order. Finally, the fourth and fifth sets of planned comparisons examined whether imitating the *atypical* model in a fixed trial order facilitated sensorimotor planning and learning in autism. For sensorimotor planning, imitation during the late-acquisition block (fixed order trial) was compared against the post-test (randomised trial order). If voluntary imitation differences in autism are specifically related to sensorimotor integration, rather than planning, it is expected that there will be no significant change in imitation performance from the late-acquisition block to the post-test. For sensorimotor learning, imitation during the pre-test (randomised trial order) was

compared against the post-test (randomised trial order). If imitating in a fixed trial order facilitates sensorimotor adaptation and the refinement of an internal action model, a significant change in imitation performance between the pre-test and post-test phases of the experiment is expected.

4.2 Method

Participants

Twenty *control* participants (15 male; 5 female) and 20 *autistic* participants (15 male; 5 female) volunteered for the study. The participants were recruited from an autistic society in North West England, and the host University. The participants were provided with a participant information sheet and given the opportunity to consent to be part of the study. All consenting participants were screened via self-report for the following exclusion criteria: dyspraxia, dyslexia, epilepsy and other neurological or psychiatric conditions. The 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 social interaction subscales. Groups were equated for age, as well as full-scale, verbal and performance IQ, which was measured via the Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999). Sample 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: Characteristics of autism and control participants.

	Autism (n = 20)		Control (n = 20)		t test p value
	Mean (SD)	Range	Mean (SD)	Range	
Chronological age in years	27 (8)	18-48	25 (8)	18-46	$p = 0.509$
Full scale IQ	110 (10)	93-129	110 (10)	85-128	$p = 0.893$
Verbal IQ	112 (12)	87-134	111 (8)	92-122	$p = 0.858$
Performance IQ	106 (10)	89-123	105 (10)	82-128	$p = 0.803$
Gender	15M : 5F		15M : 5F		

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 900 mm. Connected to the monitor was a desktop PC (Hewlett Packard Compaq 8000), graphics tablet and a hand-held stylus (Wacom Intuos Pro XL). Experimental stimuli were generated on the host 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.). Movement of the left eye was recorded at 250 Hz using an EyeLink eye tracker (SR Research) with remote optics. The host PC and EyeLink were synchronized using a TTL signal.

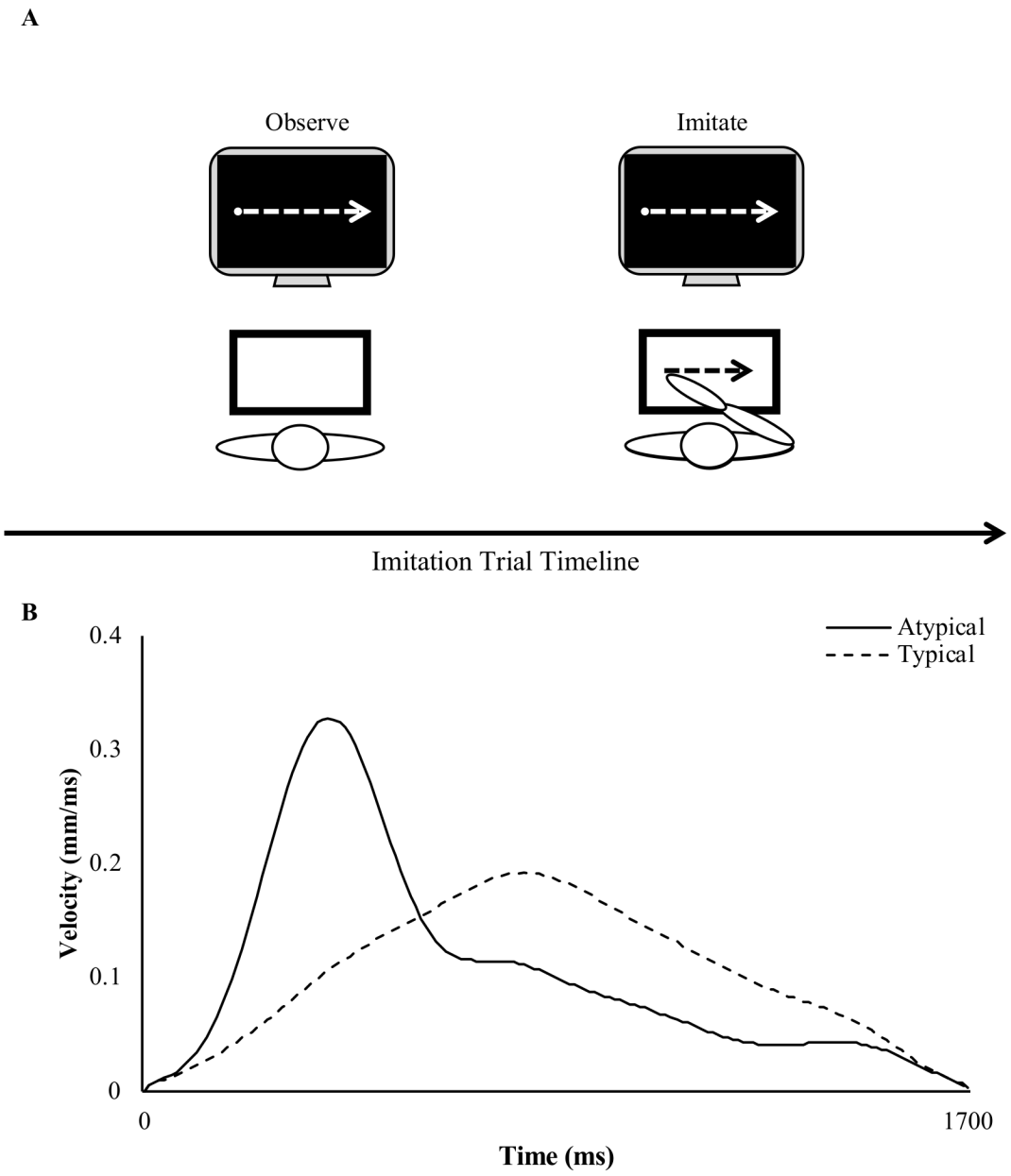

Figure 4.1: (A) A schematic representation of the laboratory/experimental set-up for the imitation task. The black outlined rectangle represents a graphics tablet. The white circle displayed on the CRT monitor represents the model. The single-segment movement is depicted by the arrow (i.e., from the start position to the final position). (B) Displacement time-series displaying typical (dark-grey trace) and atypical (black trace) velocity models.

Stimuli

To examine the imitation of biological kinematics, participants observed non-human agent models that displayed a single white-dot (diameter = 6.25 mm) that

moved from the home-position on the left-hand side of the screen to the right-hand end-position (*Figure 4.1.A*). The movement occurred in the horizontal axis only, with an amplitude of 200 mm and total duration of 1700 ms. Two models, which were created by a human volunteer, displayed typical or atypical velocity profiles. The typical model displayed a typical (Elliott et al., 2010; Flash & Hogan, 1985) bell-shaped velocity profile (displacement time-series is displayed as the dark grey trace in *Figure 4.1.B*) that had a magnitude of peak velocity that was 0.19 mm/ms and a peak that occurred at 44 % of the movement duration. The atypical model (black trace in *Figure 4.1.B*) had a magnitude of peak velocity that was 0.33 mm/ms that occurred at 18 % of the movement duration. The method of using a human volunteer to generate both models was critical because it ensured the kinematics were biological and could be reproduced by the participants.

Procedure

The imitation task consisted of a pre-test, followed by an acquisition phase and a post-test. The initial pre-test consisted of 12 trials (6 *atypical*, 6 *typical*) presented in a randomised order that reduced the predictability of an upcoming model. In the acquisition phase, both groups performed 60 imitation practice trials where each model was presented in a fixed-trial order within a block of 30 trials. The presentation order of the block of *typical* and *atypical* models was counterbalanced across participants. This fixed-trial order was used to allow participants to generate and update an internal action model on a trial-by-trial basis. Finally, participants completed a post-test that replicated the procedure of the pre-test.

Prior to the experimental phases, all participants completed four familiarisation trials that replicated the conditions of the imitation task. Each trial began with a model positioned in the home-position at the left-side of the display,

after which it moved to the end-position with a constant velocity. The constant velocity model displayed the exact movement duration and amplitude of the experimental models but moved with a constant velocity in the horizontal x axis (0.12 mm/ms). This model ensured construct validity by preventing participants experiencing biological kinematics before the imitation trials. Participants were not informed about the duration of the movement or the different type of stimuli. After observing the model, participants imitated by moving the stylus on the tablet so that the cursor moved from the home-position to the end-position as per the movement displayed by the model. All participants verbally confirmed to an experimenter they understood the model, the instruction to imitate the model, and the sensorimotor association between the stylus on a graphics tablet and the corresponding movement of the cursor on the monitor. Recording of eye movements was performed for all trials (54 trials).

Data Reduction

Behavioural Data:

To quantify imitation of movement kinematics the analysis was focussed on x-axis data only (Hayes, Andrew, Elliott, Roberts, & Bennett, 2012; Hayes et al., 2010, 2013; Hayes et al., 2014). The perpendicular deviation in the y-axis for the atypical model and typical model was minimal as confirmed by a root mean square error of 0.9 mm for the atypical model and 1.55 mm for the typical model. The start and end of the movement was identified within the x-axis position data. The start was defined as the moment the centre of the cursor moved beyond the perimeter of the home-position, and end equated to the moment the participant clicked the upper-button on the stylus. 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 central difference algorithm to obtain velocity. A MATLAB routine extracted percentage-time-to-peak-hand-velocity (*tPHV*) from each trial. This kinematic dependent variable was chosen as it provides a discrete measure that accurately reflects whether participants imitate the magnitude and timing characteristics of the observed biological kinematics (Hayes et al., 2014).

Eye Movement Data:

To quantify eye behaviour during the action-observation phase of imitation the analysis focussed on the x-axis data recorded from the left-eye. Synchronisation signals (TTL from host computer) were used to identify the start and end of stimulus presentation and the corresponding eye movement during each trial. Saccades were identified in the x-axis eye position data using the proprietary algorithm in the EyeLink software. The criterion for saccade identification was a velocity threshold of 30 deg/s, acceleration threshold of 8000 deg/s2, and a motion threshold of 0.15 deg. Saccades plus an additional five data points (equivalent to 20 ms) at the beginning and end of the identified saccade trajectory were then removed from the eye velocity trace. The removed data were replaced by a linear interpolation routine based on the smooth eye velocity before and after the saccade (Bennett & Barnes, 2003). The desaccaded smooth eye velocity was then low-pass filtered using a moving average zero-phase filter (40 ms window). To quantify how well the eye matched the velocity trajectory of the observed model percentage-time-to-peak-smooth-eye-velocity (*tPSEV*) was extracted for each trial. The latter measure was analogous to that described above for the analysis of hand kinematics.

Data Analysis

For all dependent variables, intra-participant means were calculated from the kinematic data in the imitation phases, and from the eye movement data in the action-observation phases. For the pre-test and post-test, means were calculated from the 6 trials performed during the imitation of *atypical*, and *typical* biological kinematics. For acquisition, means were calculated from trials that represented the early (1-6), middle (13-18) and late (25-30) stages of acquisition. In order to examine the *a priori* questions associated with imitation learning, each dependent variable was first submitted to a separate 2 Group (*autism*; *control*) x 2 Model (atypical; typical) x 5 Phase (pre-test; early-acquisition; middle-acquisition; late-acquisition; post-test) mixed design ANOVA. The 5 sets of orthogonal planned comparisons to address specific a priori hypotheses/questions were then conducted for each dependant variable. The first set of planned comparisons are associated with variance pooled from all phases of the imitation protocol. The second set of separate planned comparisons compared imitation behaviour from the pre-test (random-trial order) to middle-acquisition (fixed-trial order) for the *autism* and *control* groups. The third set of planned comparisons examined imitation behaviour across acquisition by comparing early-acquisition (fixed-trial order) against the pooled behaviour of the middle/late-acquisition (fixed-trial order) for the *autism* and *control* groups. The fourth set of planned comparisons examined imitation behaviour from the late stage (fixed-trial order) of acquisition to the post-test (random-trial order). The final set of planned comparisons investigated learning by examining imitation behaviour from the pre-test (random-trial order) to the post-test (random-trial order). Alpha was set at $p < 0.05$.

4.3 Results

Percentage-time-to-peak-hand-velocity (tPHV)

ANOVA revealed a significant main effect of group [F (1, 38) = 7.05, p < 0.05, η_p^2 = 0.156], a significant main effect of model [F (1, 38) = 62.11, p < 0.001, η_p^2 = 0.620], and a significant model x phase interaction [F (4, 152) = 2.55, p < 0.05, η_p^2 = 0.063]. No other significant main and/or interaction effects were present.

tPHV data for both groups across all phases of the imitation learning protocol are illustrated in *Figure 4.2* (A: *atypical*; B: *typical*). The first set of planned comparisons are associated with variance pooled from all phases of the imitation protocol. First, there was a significant difference in general imitation behaviour between the *autism* and *control* groups [F (1, 38) = 7.05, p < 0.05]. When examining imitation across the two models, the *autism* [F (1, 38) = 17.95, p < 0.001] and *control* [F (1, 38) = 47.73, p < 0.001] groups showed significant differences in behaviour when imitating the *atypical* (*autism* M = 28.46 ± 8.98; *control* M = 20.99 ± 7.67) and *typical* (*autism* M = 36.76 ± 9.88; *control* M = 34.52 ± 9.29) models.

The second set of separate planned comparisons compared imitation behaviour from the pre-test (random-trial order) to middle-acquisition (fixed-trial order) for the *autism* and *control* groups. Middle-acquisition was selected as it was deemed an appropriate stage to examine sensorimotor adaptation following half the imitation practice trials. For the *control* group, there was no significant differences in behaviour when imitating either model across the two phases [*atypical*: F (1, 38) = 0.40, p > 0.05; *typical*: F (1, 38) = 0.09, p > 0.05]. The percentage change when imitating the *atypical* model was %Δ = 5, and the *typical* model was %Δ = 2. Although the *autism* group demonstrated no significant change (%Δ = 2) in behaviour when imitating the *typical* model [F (1, 38) = 0.11, p > 0.05], there was a significant change (%Δ = 17) leading to peak velocity occurring earlier in the movement when imitating the *atypical* model [F (1, 38) = 9.47, p < 0.01].

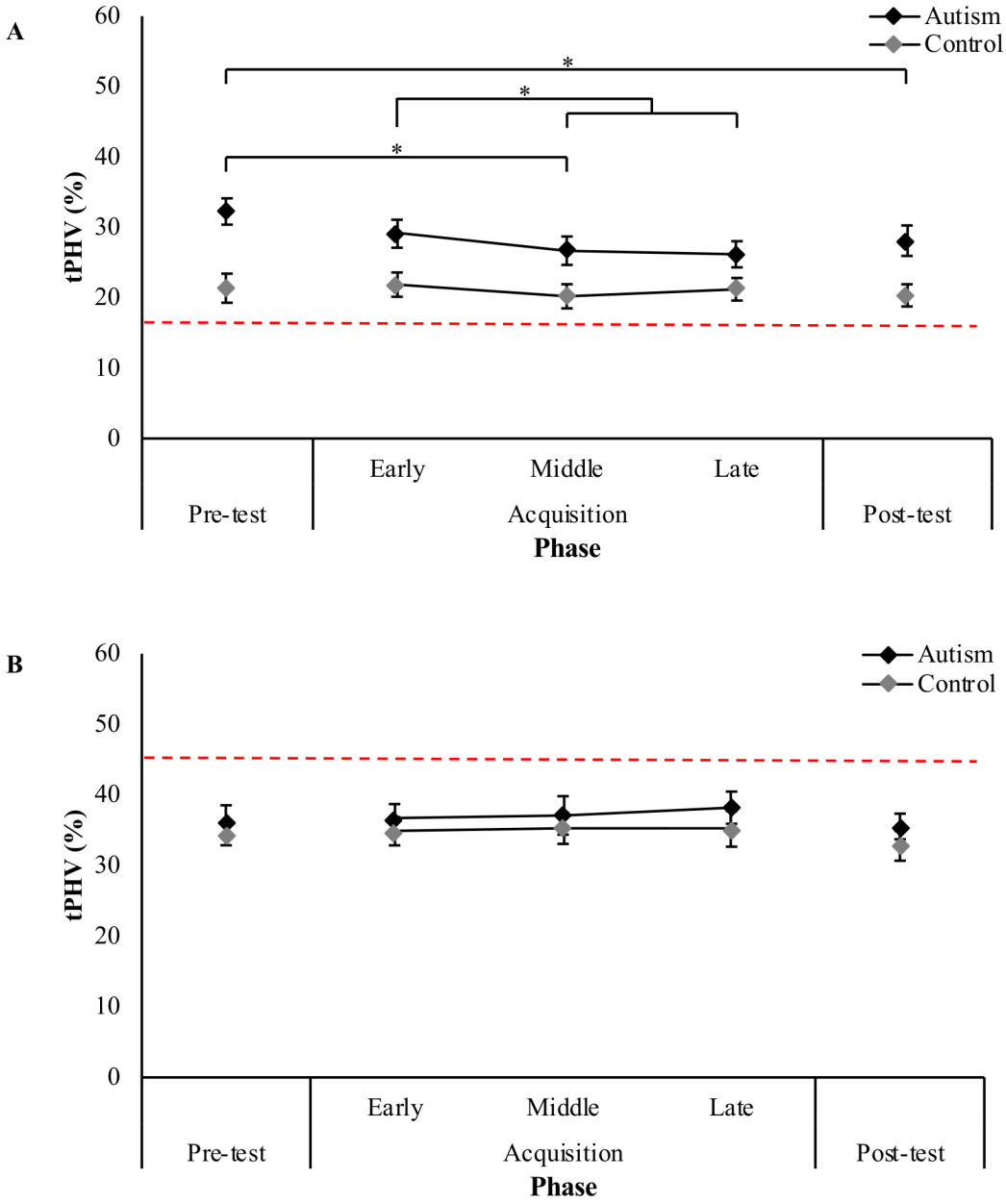

Figure 4.2: Percentage-time-to-peak-hand-velocity for the imitation task (error bars represent standard error of the mean) presented as a function of group and phase for the atypical model (A) and the typical model (B). Dashed line represents the model.

The third set of planned comparisons examined imitation behaviour across acquisition by comparing early-acquisition (fixed-trial order) against the pooled behaviour of the middle/late-acquisition (fixed-trial order) for the *autism* and *control* groups. There were no significant changes across these phases for the *control* group when imitating either model [*atypical*: $F(1, 38) = 0.88$, $p > 0.05$; *typical*: $F(1, 38) =$

0.04, p > 0.05]. The percentage change when imitating the *atypical* model was %Δ = 5, and the *typical* model was %Δ = <1. Although the *autism* group demonstrated no significant change (%Δ = 2) in behaviour when imitating the *typical* model [F (1, 38) = 0.26, p > 0.05], there was a significant change (%Δ = 9) leading to peak velocity occurring earlier in the movement when imitating the *atypical* model [F (1, 38) = 4.62, p < 0.05].

The fourth set of planned comparisons examined imitation behaviour from the late stage (fixed-trial order) of acquisition to the post-test (random-trial order). There were no significant changes across these phases for the *control* group [*atypical*: F (1, 38) = 0.67, p > 0.05; *typical*: F (1, 38) = 2.11, p > 0.05] and *autism* group [*atypical*: F (1, 38) = 3.29, p > 0.05; *typical*: F (1, 38) = 2.60, p > 0.05] when imitating either model. The percentage change when imitating the *atypical* model was %Δ = 7 for *autism* group and %Δ = 4 for the *control* group. When imitating the *typical* model, the *autism* group showed %Δ = 7, and the *control* group %Δ = 7.

The final set of planned comparisons investigated learning by examining imitation behaviour from the pre-test (random-trial order) to the post-test (random-trial order). There was no overall learning effect in the *control* group for either model [*atypical*: F (1, 38) = 0.38, p > 0.05; *typical*: F (1, 38) = 0.43, p > 0.05]. Although the *autism* group showed no learning of the *typical* model [F (1, 38) = 0.07, p > 0.05], they demonstrated a significant learning effect for the *atypical* model [F (1, 38) = 6.29, p < 0.05]. The percentage change when imitating the *atypical* model was %Δ = 13 for *autism* group and %Δ = 5 for the *control* group. When imitating the *typical* model, the *autism* group showed %Δ = 2, and the control group %Δ = 5.

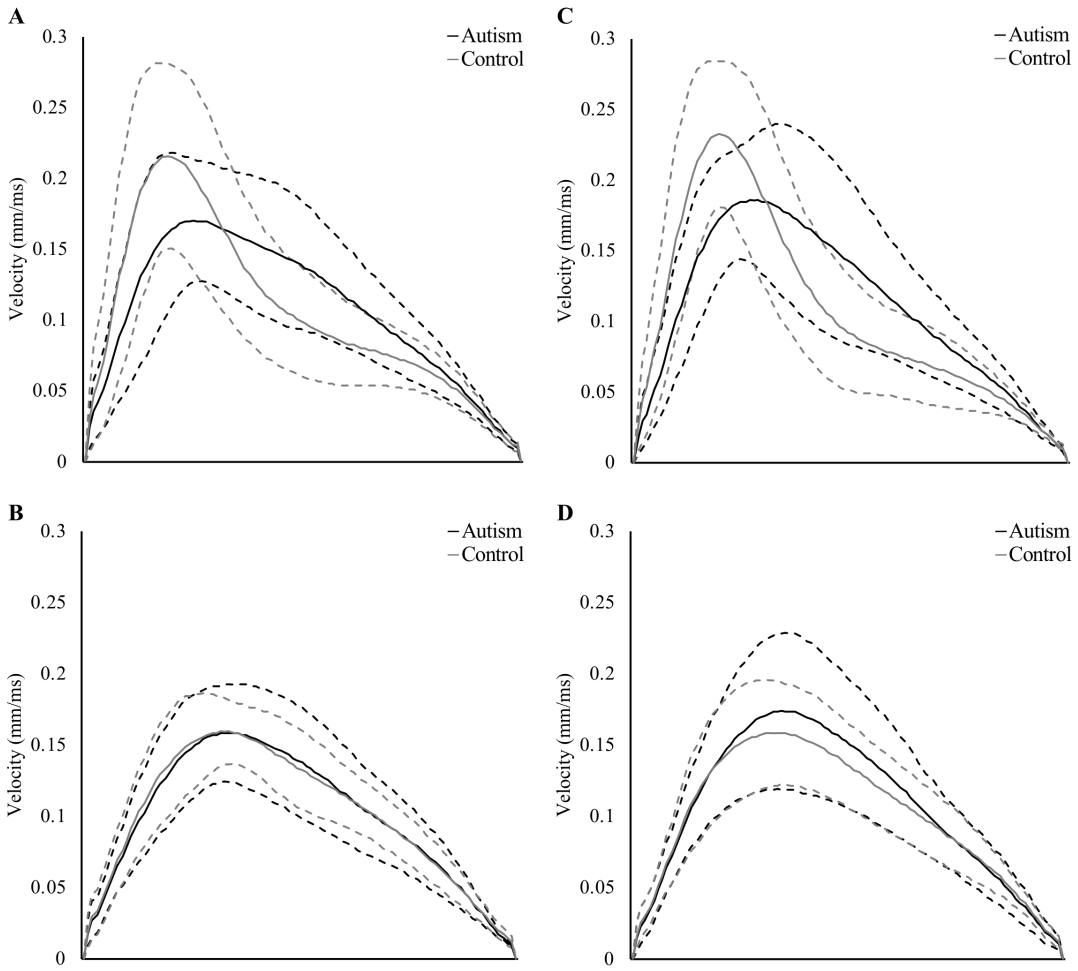

Figure 4.3: Mean velocity traces for the autism (black traces) and control (grey traces) during the pre-test (atypical: A; typical B) and the post-test (atypical: C; typical D). Dashed traces represent standard deviation of the mean.

Percentage-time-to-peak-smooth-eye-velocity (tPSEV)

ANOVA revealed a significant main effect of model [F (1, 38) = 406.57, p < 0.001, η_p^2 = 0.933], but no significant main effect of group [F (1, 29) = 0.05, p > 0.05, η_p^2 = 0.002]. Additionally, no other significant main and/or interaction effects were present.

tPSEV data for both groups across all phases of the imitation learning protocol are illustrated in *Figure 4.3* (A: *autism*; B: *control*). The first set of planned comparisons are associated with variance pooled from all phases of the imitation protocol. First, there was no significant difference in *tPSEV* when examining

behaviour at the group level [F (1, 29) = 0.04, p > 0.05]. When examining *tPSEV* as a function of observing the different models, the *autism* [F (1, 29) = 169.93, p < 0.00] and *control* [F (1, 29) = 243.44, p < 0.001] groups showed significant differences in behaviour when observing the *atypical* (*autism* M = 31.67 ± 6; *control* M = 30.37 ± 4.03) and *typical* (*autism* M = 50.55 ± 7.55; *control* M = 52.25 ± 5.03) models.

The second set of separate planned comparisons compared *tPSEV* from the pre-test (random-trial order) to middle-acquisition (fixed-trial order) for the *autism* and *control* groups. There were no significant changes across these phases when observing either model for the *control* group [*atypical*: F (1, 29) = 0.05, p > 0.05; *typical*: F (1, 29) = 0.001, p > 0.05] or the *autism* group [F (1, 29) = 0.18, p > 0.01; *typical*: F (1, 29) = 2.31, p > 0.05]. The percentage change for the *control* group when observing the *atypical* model was %Δ = 1, and the *typical* model was %Δ = <1, and for the *autism* group when observing the *atypical* model was %Δ = 2, and the *typical* model was %Δ = 6.

The third set of planned comparisons examined *tPSEV* across acquisition by comparing early-acquisition (fixed-trial order) against the pooled behaviour of the middle/late-acquisition (fixed-trial order) for the *autism* and *control* groups. There were no significant changes across these phases when observing either model for the *control* group [*atypical*: F (1, 29) = 0.15, p > 0.05; *typical*: F (1, 29) = 0.83, p > 0.05] or the *autism* group [*atypical*: F (1, 29) = 3.55, p > 0.05; *typical*: F (1, 29) = 0.001, p > 0.05]. The percentage change for the *control* group when observing the *atypical* model was %Δ = 3, and the *typical* model was %Δ = 2, and for the *autism* group when observing the *atypical* model was %Δ = 13, and the *typical* model was %Δ = < 1.

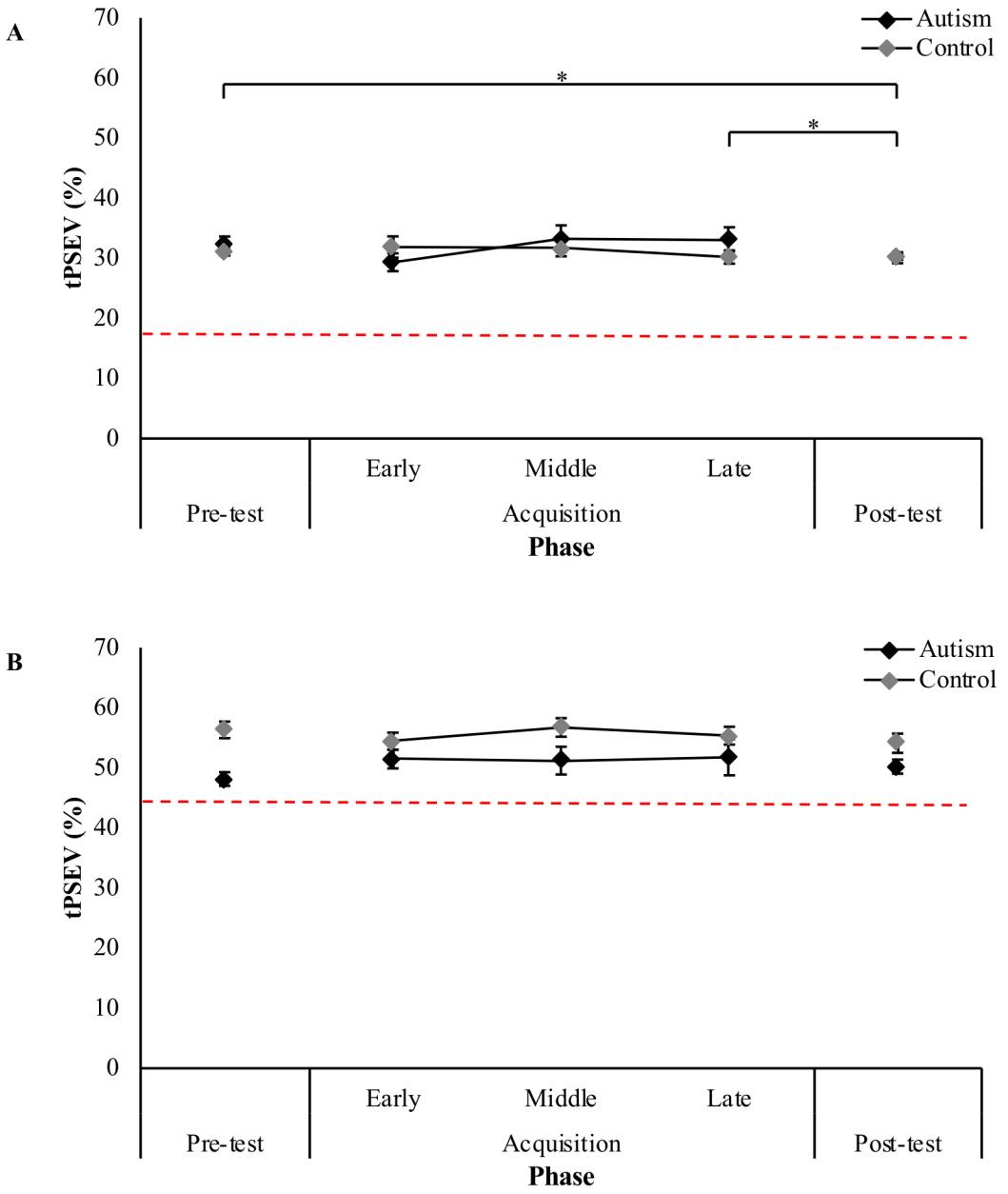

Figure 4.4: Percentage-time-to-peak-smooth-eye-velocity during the imitation task (error bars represent standard error of the mean) presented as a function of group and phase for the atypical model (A) and the typical model (B). Dashed line represents the model.

The fourth set of planned comparisons examined *tPSEV* from the late stage (fixed-trial order) of acquisition to the post-test (random-trial order). When observing the *atypical* model, *tPSEV* occurred earlier (%Δ = 9) for the *autism* group in the post-test compared to the late stage of acquisition [$F(1, 29) = 4.31$, $p < 0.05$]. The *autism* group did not demonstrate a significant change (%Δ = 3) when observing

the *typical* model [F (1, 29) = 0.53, p > 0.05]. There were no significant changes across these phases when observing either model for the *control* group [*atypical*: F (1, 29) = 0.01, p > 0.05; *typical*: F (1, 29) = 0.34, p > 0.05]. The percentage change when observing the *atypical* model was %Δ = < 1, and the *typical* model was %Δ = 2.

The final set of planned comparisons investigated learning by examining *tPSEV* from the pre-test (random-trial order) to the post-test (random-trial order). When observing the *atypical* model, peak-smooth-eye-velocity occurred earlier (%Δ = 8) for the *autism* group in the post-test compared to the pre-test [F (1, 29) = 6.75, p < 0.05]. The *autism* group did not demonstrate a significant change (%Δ = 4) when observing the *typical* model [F (1, 29) = 2.06, p > 0.05]. There were no significant changes across these phases when observing either model for the *control* group [*atypical*: F (1, 29) = 0.70, p > 0.05; *typical*: F (1, 29) = 2.25, p > 0.05]. The percentage change when observing the *atypical* model was %Δ = 3, and the *typical* model was %Δ = 4.

4.4 Discussion

Although voluntary imitation is generally different in autistic individuals compared to matched-controls (DeMyer et al., 1972; Rogers & Pennington, 1991; Vivanti & Hamilton, 2014), there is evidence that certain sensorimotor processes underlying imitation are operational (Bird et al., 2007; Hamilton et al., 2007; Hayes, Andrew, et al., 2016). Therefore, to better understand the function of these processes, this study was designed with five *a priori* hypotheses that logically and conceptually tested (via orthogonal planned comparisons) separate aspects of imitation behaviour when autistic and control volunteers learned to imitate novel *atypical* biological kinematics.

The first set of planned comparisons confirmed a general difference in imitation behaviour between autistic and matched-control groups, thereby suggesting certain sensorimotor processing operations in autism impact the efficacy of how novel actions are imitated (DeMyer et al., 1972; Hayes, Andrew, et al., 2016; Hobson & Lee, 1999; Rogers et al., 1996; Stewart et al., 2013; Wild et al., 2012). Nonetheless, both groups did scale hand and eye kinematics such that peak velocity occurred earlier in the movement trajectory when imitating the *atypical* compared to *typical* model. As well as replicating previous findings in matched-control participants (Andrew et al., 2016; Hayes, Dutoy, et al., 2016), this is the first evidence showing that autistic individuals can imitate novel *atypical* biological kinematics that would not have existed in their motor repertoire.

More importantly, the second and third sets of planned comparisons suggest the imitation of *atypical* kinematics in autism is underpinned by processes that facilitate sensorimotor integration and adaptation. Compared to the control group that successfully imitated the *atypical* model at pre-test and middle-acquisition (second planned comparison), the autism group exhibited a significant 17% change (5 units of *tPHV*) in imitation behaviour by the time they had the opportunity to perform the task in the fixed trial order during middle-acquisition. The third planned comparison, which examined changes in imitation from early-acquisition to middle/late-acquisition where trials were received in fixed trial order, indicated that the autism group significantly adapted *tPHV* by 9%. These comparisons indicate that the adaptation effects were not merely a result of switching the learning environment from a randomised to fixed trial order. In addition, the fact this change was not shown in previous work (Hayes, Andrew, et al., 2016) where a group of comparable autistic adults imitated *atypical, typical* and *constant velocity* kinematics presented

randomly across 84 trials, indicates that the adaptation effect found here is unlikely to be a result of general practice.

Together with the aforementioned previous work, the findings of the current study indicate that adaptation was underpinned by the way the fixed trial order engaged the underlying sensorimotor processes over repeated attempts at imitating the *atypical* kinematics. More specifically, this suggests the fixed trial order facilitated voluntary imitation by optimising sensorimotor control and integration processes engaged to specify the forces required to initially execute the movement. In addition, by keeping sensorimotor information similar between consecutive trials, the comparison and processing of expected (efference copy; feedforward control) and actual (reafference; feedback control) sensorimotor consequences from trial *n* can be integrated more effectively. This optimises feedforward and feedback control mechanisms during motor execution (Kantak & Winstein, 2012), and subsequent sensorimotor consolidation and planning for trial *n+1* (Elliott et al., 2001; Wolpert et al., 2011). Therefore, repeated imitation trials presented in a fixed trial order enables an internal action model to be refined and encoded so that the imitated movement became similar to the *atypical* biological kinematics displayed by the model.

Further evidence that sensorimotor adaptation was optimised by facilitating the integration and encoding of *atypical* biological kinematics is apparent from the fourth and fifth sets of planned comparisons. The fourth set indicated no significant changes in behaviour for either group when imitation was compared from late-acquisition (fixed trial order) to the post-test (randomised trial order). This is in contrast to the significant change found in the fifth set, where the autism group successfully imitated the *atypical* kinematics at post-test compared to pre-test. These combined effects indicate the processing changes that occurred during the fixed trial order underpinned the encoding of an internal action model that was operational

when the autism group was transferred to the randomised trial order reintroduced in the post-test. This learning effect revealed that differences in voluntary imitation in autism (DeMyer et al., 1972; Rogers & Pennington, 1991; Vivanti & Hamilton, 2014) are not solely related to sensorimotor planning problems (Glazebrook et al., 2006; Rinehart et al., 2001) associated with imitating a novel action (Hayes, Andrew, et al., 2016; Stewart et al., 2013; Wild et al., 2012) otherwise positive transfer would not have been shown. Rather, the underlying visuomotor system activated during voluntary imitation in autism is functional, but operational imitation of *atypical* biological kinematics requires a learning environment that facilitates sensorimotor integration.

The sensorimotor integration interpretation is supported by the eye movement data. First, both groups scaled smooth pursuit eye velocity to the different models [*atypical* (*autism* M = 32; *control* M = 30); *typical* (*autism* M = 51; *control* M = 52)]. Second, neither group significantly changed smooth pursuit eye velocity when imitating the *atypical* model in the pre-test (random trial order) compared to middle-acquisition (fixed trial order), nor from early-acquisition to middle/late-acquisition (NB. both had fixed trial order). These data show that the high-acuity region of the fovea during pursuit, which coincides with overt visual attention, was maintained within the vicinity of the observed model(s) irrespective of trial order. Consequently, the changes in imitation of the *atypical* model are unlikely to be related to eye movements, which in fact would have provided similar retinal and extra-retinal input required for processing *atypical* biological kinematics for limb configuration.

In summary, voluntary imitation has received a great deal of attention in the investigation of autism following the suggestion that deficits in the underlying processes (Stewart et al., 2013; Williams et al., 2001) attenuate the acquisition of

important social and motor skills. By systematically controlling for overt visual attention and sensorimotor planning in the present study, this study has shown that the imitation difficulties in autism (pre-test effects for the autism group) are in part related to sensorimotor processing and integration atypicalities. Importantly, however, these findings suggest that these atypicalities in the autistic sensorimotor system can be modulated by structuring the voluntary imitation environment in a predictable manner such that it facilitates trial-to-trial sensorimotor processing, integration and encoding of *atypical* biological motion. To conclude, this positive voluntary imitation effect extends upon the evidence that confirmed goal-directed imitation (Hamilton et al., 2007; Subiaul et al., 2007) and automatic imitation (Bird et al., 2007; Press et al., 2010) are operational in autism.

5 Chapter Five: Observational Practice of Atypical Biological Kinematics in Autism Spectrum Disorders.

5.1 Introduction

Humans have an exceptional ability to learn new sensorimotor behaviours by observing and imitating another person performing an action. When an action is novel, and therefore not part of an existing sensorimotor repertoire, a new internal action model is learned by engaging intentional, attentional and sensorimotor processes. During voluntary imitation (henceforth imitation), an individual observes a model that typically prescribes a higher-order action-goal (e.g., to use chop sticks; to pick up noodles), and the lower-level kinematic properties (e.g., velocity of the digits) that constrain the means of achieving the action-goal. During action-observation, information regarding the action-goal and lower-level biological properties are encoded (Heyes, 2010) as a representation within a sensorimotor system directly linking perception-to-action (Prinz, 1997). After action-observation, sensorimotor planning processes generate an inverse model from the representation encoded via action-observation in order to form a motor plan required to execute the action. During, and after, movement execution, efferent and reafferent sensorimotor information is integrated and processed by feedforward and feedback control mechanisms (Desmurget & Grafton, 2000; Elliott et al., 2010; Wolpert & Flanagan, 2010) to support encoding. Over repeated imitation trials, an action-representation is refined so that an imitated movement becomes similar to the observed biological motion characteristics displayed by the model.

Although the sensorimotor processes underlying imitation are learned and operational from infancy (Oostenbroek et al., 2016), it has been shown that autistic individuals successfully imitate actions that involves observing models interacting with objects (Hamilton, Brindley, & Frith, 2007; Vivanti et al., 2011; Vivanti, Nadig, Ozonoff, & Rogers, 2008), but exhibit a specific difficulty when observing and imitating body (biological kinematic properties) movements performed by a

model (Bernier, Dawson, Webb, & Murias, 2007; DeMyer et al., 1972; Hayes, Andrew, Elliott, Gowen, & Bennett, 2016; Hobson & Lee, 1999; Rogers, Bennetto, McEvoy, & Pennington, 1996; Stewart, McIntosh, & Williams, 2013; Vanvuchelen, Roeyers, & De Weerdt, 2007; Wild, Poliakoff, Jerrison, & Gowen, 2012). For example, in an examination of the imitation of biological kinematics, two point-light models that displayed the same movement amplitude and time, but different underlying kinematics (Hayes et al., 2016) were randomly presented across imitation trials. An experimental model displayed novel atypical kinematics where peak velocity occurred at 18% of the movement trajectory, and therefore required participants to learn to represent the kinematics in order to reorganise the sensorimotor system to execute a correct motor response. A control model displayed typical kinematics that had a bell-shaped velocity profile, and could be imitated by rescaling a movement from an existing motor repertoire (Carmo, Rumiati, Siugzdaite, & Brambilla, 2013; Rumiati et al., 2005). Importantly, participants received verbal task instructions to 'imitate the movement of the model', therefore creating a learning context that was prescriptive, rather than imitation being spontaneous (Charman et al., 1997). Point-light model stimuli were used to remove/control social (i.e., social features are removed from the model; Chartrand & Bargh, 1999) and goal-directed (i.e., the model moved to space, not to an end-state-target-goal; Bekkering, Wohlschlager, & Gattis, 2000) information that is known to modulate imitation. As expected, there was no difference between autism and control groups when imitating the control model. However, unlike the control group that successfully imitated the atypical kinematics (Hayes et al., 2016), the autism group reproduced a movement with a typical kinematic profile. That said, they did become significantly more accurate and consistent at reproducing the temporal property of the modelled movement (i.e., the criterion movement time goal of 1700 ms), which

indicates they were actively engaged in the process of imitation, and showed adaptation across learning. Taken together, it would seem that while certain top-down attentional learning processes underlying imitation are operational in autism (see also Vivanti & Hamilton, 2014), the autistic participants show a specific difficulty imitating the atypical biological kinematics (see also Stewart et al., 2013; Wild et al., 2012).

This specific difficulty was suggested to be related to the randomised trial order impacting sensorimotor planning (Glazebrook, Elliott, & Lyons, 2006; Mari, Castiello, Marks, Marraffa, & Prior, 2003; Rinehart et al., 2006), sensorimotor integration (Marko et al., 2015; Nebel et al., 2016) and motor execution (J. Cook, Blakemore, & Press, 2013; Glazebrook, Gonzalez, Hansen, & Elliott, 2009), as well as the consolidation of these phases into an effective sensorimotor representation. For example, sensorimotor information from trial *n* (e.g., *atypical* model) can be different to trial *n+1* (e.g., *typical* model), thus limiting the refinement of a sensorimotor representation by comparing expected (e.g., what was imitated on trial *n*, and information from action-observation on trial *n+1*) and actual (reafferent) sensorimotor consequences from trial *n* over dissimilar trial types (Desmurget & Grafton, 2000; Elliott et al., 2010; Wolpert, Diedrichsen, & Flanagan, 2011). Rather than imitated movements being consolidated and refined, the process of repeatedly constructing and reconstructing (Cross, Schmitt, & Grafton, 2007) different representations induces interference between trials (Shea & Morgan, 1979), which modulates sensorimotor integration leading to attenuated movement reproduction (Lin et al., 2009). Moreover, data from behavioural studies (Haswell, Izawa, Dowell, Mostofsky, & Shadmehr, 2009; McDuffie et al., 2007; Vanvuchelen et al., 2007) showing associations between motor behaviour (i.e., greater reliance on proprioception) and imitation (i.e., greater number of incorrect gestures imitated)

performance (Haswell et al., 2009) and neuropsychologically (Nebel et al., 2016) where better imitators (greater number of correct gestures) demonstrated greater intrinsic synchrony between visual (i.e., higher-order visual processing areas) and motor (i.e., motor regions) networks has led to the suggestion that autism specific visual-motor functional connectivity disrupts the integration of visual input with motor output (Mostofsky & Ewen, 2011; Nebel et al., 2016) leading to attenuated imitation.

The difficulty in reproducing modelled actions (human, and non-biological stimulus, models) has also been suggested (Stewart et al., 2013) to be related sensorimotor integration, with a specific disruption within self-other mapping processes that directly integrates observed visual information (e.g., biological kinematics) during the action-observation (i.e., input measured by EEG and fMRI) phase of imitation (Bernier et al., 2007; Dapretto et al., 2006; Martineau, Andersson, Barthélémy, Cottier, & Destrieux, 2010; Oberman et al., 2005; Oberman, Ramachandran, & Pineda, 2008; Williams et al., 2006). There is, however, strong evidence from automatic imitation reaction time studies that self-other visuomotor mapping is operational in autism (Bird, Leighton, Press, & Heyes, 2007; Edey et al., 2016; Hamilton et al., 2007; Press, Richardson, & Bird, 2010; Schulte-Rüther et al., 2017; Sowden, Koehne, Catmur, Dziobek, & Bird, 2016; Spengler, Bird, & Brass, 2010). Because automatic imitation protocols limit the contribution of other associated (i.e., motor control) processes that can affect movement reproduction in autism, the automatic response priming (Brass, Bekkering, & Prinz, 2001) in correspondence to the observed movement indicates functional perception-action matching, where the stimulus prespecifies perceivable consequences of the action. In addition to automatic imitation, predictive eye tracking that quantifies the relationship between performed and observed hand actions is indicative of the

functionality of the execution/observation matching system (Hamilton, 2013). Compared to control participants, data from eye tracking studies show that while autistic participants exhibit differences when attending to social (e.g., faces) cues (Falck-Ytter, Fernell, Hedvall, von Hofsten, & Gillberg, 2012; Vivanti et al., 2008), they demonstrate comparable attention and eye behaviour when viewing hand actions (Falck-Ytter, 2009; Vivanti et al., 2011; Vivanti et al., 2008). The similarities in predictive eye gaze is suggestive of an operational matching-system supporting the observation of actions in autism (Hamilton, 2013).

In this study, the contribution of sensorimotor integration during imitation of atypical biological kinematics in autism was examined using a repeated-measures design that comprised an 'observational practice protocol (OPp)' followed by an 'imitation learning protocol (ILp)'. The OPp was selected because participants have previously been shown to learn novel biological movements by repeatedly observing a model across a set number of trials (Bird, Osman, Saggerson, & Heyes, 2005; Hayes, Roberts, Elliott, & Bennett, 2014). Unlike imitation, that requires trial-to-trial observation-execution, observational practice controls the involvement of the peripheral motor system thus limiting the contribution of sensorimotor integration (i.e., no explicit efference or reafference) during learning. Using the OPp and the ILp therefore allows the contribution of sensorimotor integration during action-observation, and sensorimotor integration during action-observation-execution, to be examined during the same study. If the differences previously reported in the efficacy of imitating non-goal-directed actions in autism are associated with a sensorimotor system that disrupts the integration of visual input with motor output, it is expected that autistic participants, along with controls, will learn to reproduce the observed atypical biological kinematics displayed by a model over observational practice as there is no active requirement to perform this sensorimotor integration.

Finally, the follow-up ILp affords an opportunity to examine the active contribution of sensorimotor integration by having a transfer condition where participants observe the same model displaying the atypical biological kinematics. If autistic and control participants do learn to reproduce the observed atypical biological kinematics over observational practice, the follow-up imitation performance should be reduced in the autistic participants if their ability to a integrate visual input with a motor output is altered.

5.2 Method

Participants

The volunteers were recruited from an autistic society in North West England, and the host University. Volunteers were provided with a participant information sheet to read, followed by an opportunity to ask questions to clarify the experimental procedures, and then a time period to consider whether they would like to consent to engage in the study. Following this process, 20 control (18 male; 2 female), and 20 autistic (18 male; 2 female) volunteers participated in the study. All participants were screened via self-report for the following exclusion criteria: dyspraxia, dyslexia, epilepsy and other neurological or psychiatric conditions. The autistic participants 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 autistic participants met the threshold for autism spectrum disorder on the ADOS-2 total classification score, and on the communication, and social interaction subscales. Groups were equated for age, as well as full-scale verbal, and performance, IQ as measured via the Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler,

1999). Participant characteristics are presented in *Table 5.1*. The experiment was designed in accordance with the 1964 declaration of Helsinki and received full approval by the host University research ethics committee.

Table 5.5.1: Characteristics of autism and control participants.

	Autism (n = 20)		Control (n = 20)		t test p value
	Mean (SD)	Range	Mean (SD)	Range	
Chronological age in years	25 (7)	18-44	25 (7)	18-45	$p = 0.845$
Full scale IQ	107 (9)	91-125	109 (8)	94-123	$p = 0.396$
Verbal IQ	106 (11)	88-130	109 (8)	96-125	$p = 0.214$
Performance IQ	106 (11)	82-128	107 (12)	82-128	$p = 0.891$
Gender	18M : 2F		18M : 2F		

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 900 mm. The monitor was connected to a desktop PC (HP Compaq 8000 Elite), which received input from a hand-held stylus on a graphics tablet (Wacom Intuos Pro XL). 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.). Movement of the left eye was recorded at 250 Hz using an EyeLink eye tracker (SR Research) with remote optics. The host PC and EyeLink were synchronized using a TTL signal.

Stimuli

To examine the acquisition of biological kinematics, participants observed two different (*typical* and *atypical* velocity profiles*; Figure 5.1.A*) white point-light dot models (diameter = 6.25 mm) presented on a black background. To create the models, a human volunteer practised performing the two aiming movements using the hand-held stylus on a graphics tablet in order to control a white-dot presented on the screen, which represented the stylus cursor, from the home position to the end position (amplitude of 200 mm) in order to exactly achieve the criterion movement time of 1700 ms. For the *typical* model, the volunteer practised performing self-selected goal-directed aiming movements in order to create a typical bell-shaped velocity profile (Elliott et al., 2010; Flash & Hogan, 1985) where the peak occurred at 44 % of the movement trajectory, and had a magnitude of peak velocity equal to 0.19 mm/ms (displacement time-series is displayed as the dashed trace in *Figure 5.1.A*). For the *atypical* model, the volunteer practised performing atypical movements in order to create a skewed velocity profile (black trace in *Figure 5.1.A*) where the peak occurred at 18 % of the movement trajectory, and had a magnitude of peak velocity equal to 0.33 mm/ms. Therefore, the time-series data used to create the two models were selected because they met the criterion movement time of 1700 ms, and displayed the two requisite *typical* and *atypical* models velocity profiles. When presented on the screen, the point-light dot models moved along a single horizontal trajectory from a home-position on the left-side of the screen to an end position at the right-side of the screen. The process of using a human volunteer to generate the models was important because the point-light dot models had a biological origin and could therefore be reproduced by the participants.

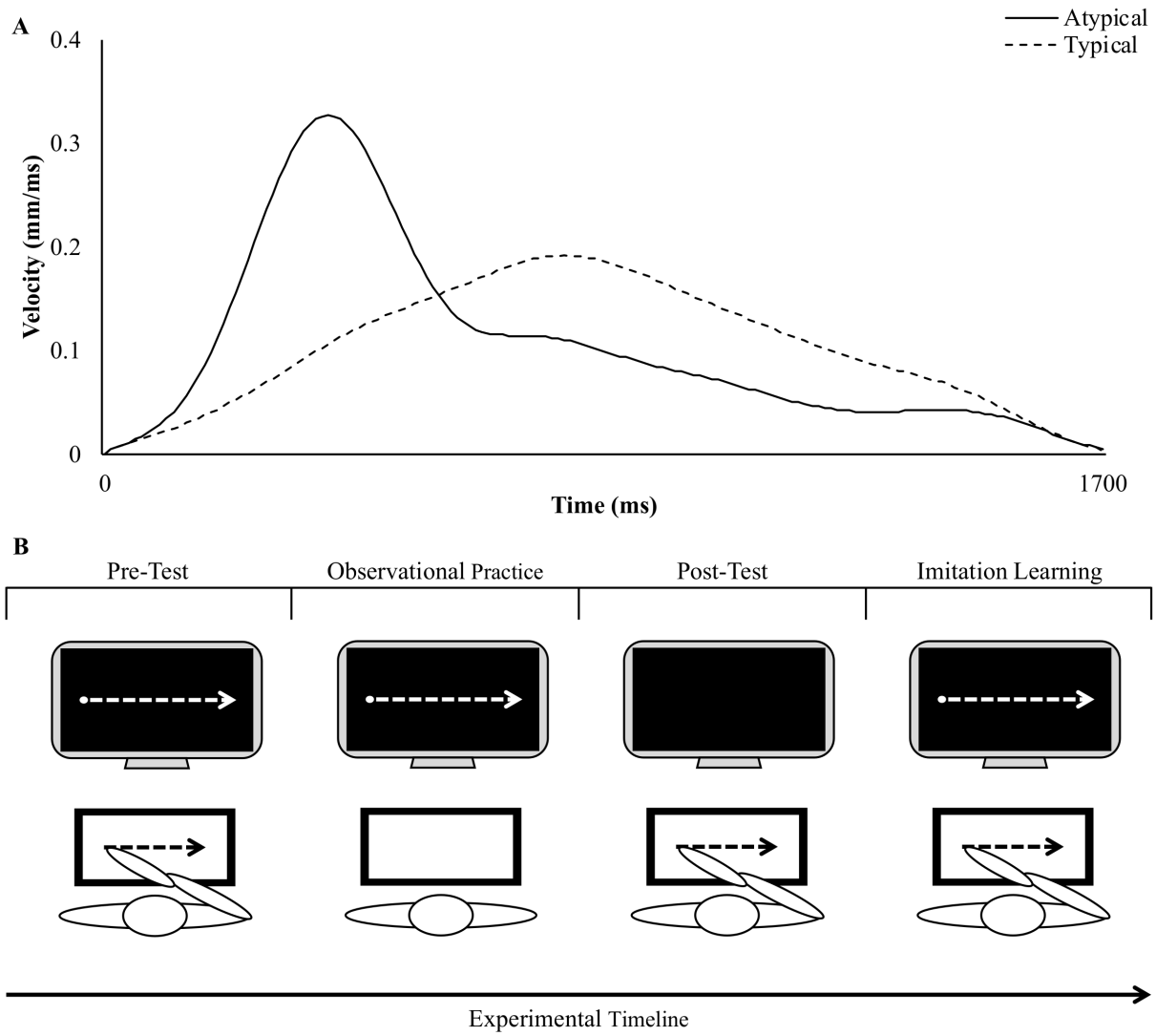

Figure 5.1: (A) Displacement time-series displaying typical (dashed trace) and atypical (black trace) velocity models. (B) A schematic representation of the experimental design. The black outlined rectangle represents a graphics tablet. The white circle displayed on the CRT monitor represents the model. The single-segment movement is depicted by the arrow (i.e., from the start position to the final position).

Procedure

Before participating in the experiment, all participants completed a familiarisation period that replicated the general methodological conditions used in the main experiment. Participants performed four imitation trials, each showing a constant velocity stimulus moving with the same movement duration (1700 ms) and amplitude (200 mm) as the experimental *typical* and *atypical* models. Importantly, velocity in the horizontal *x* axis was constant at 0.12 mm/ms, with no deviations in

the perpendicular *y* axis. This model ensured construct validity by preventing participants experiencing biological kinematics before the experimental trials. Participants were not informed about the movement duration or the nature of the stimulus type. Participants were instructed to observe the horizontal trajectory of the model with the intention to overtly reproduce the movement following action-observation. To imitate the model, the participants moved the stylus on the tablet so that the cursor moved from the home-position to the end-position as per the movement displayed by the model. All participants confirmed they observed the model, understood the instructions on how to imitate the model, and the sensorimotor association between the stylus on a graphics tablet and the corresponding movement of the cursor on the monitor.

The main experiment consisted of an observational practice protocol (OPp), followed by an imitation learning protocol (ILp) (*see Figure 5.1.B*). During the OPp, participants performed a pre-test, followed by observational practice, and a post-test. The pre-test consisted of 10 imitation trials, where on each trial participants were instructed to observe the horizontal trajectory of the *typical model* with the intention to overtly reproduce the movement following action-observation. No information was presented to the participants regarding the nature of the *typical* model. During observational practice, participants performed 30 consecutive trials of action-observation. On each trial, they were instructed to watch the movement trajectory of the model very carefully, with the intention that they would be required to imitate the observed movement from memory in the follow-up post-test. In the post-test, participants were required to execute the *atypical* velocity profile of the previously observed model from recall for 10 trials. No models were displayed in the post-test. Between the post-test and ILp all participants completed a verbal debrief session to confirm they distinguished the difference between the two models (i.e., *typical* in

pre-test, and *atypical* in observational practice), and that they had intended reproduce an *atypical* velocity profile as accurately as possible in the post-test. During the ILp both groups performed 30 imitation trials following the same protocol as the pre-test. However, during this phase only the *atypical* model was presented in a fixed-trial order. Eye movements of all participants were recorded as they observed the two stimuli during the experiment (70 trials). However, some data were subsequently excluded (7 autism; 2 control) due to recording difficulties resulting from participants wearing prescription spectacles.

Data Reduction

Behavioural Data:

Using a custom written MATLAB routine, the start and end of each movement reproduction was identified from the x-axis position data. The start was defined as the moment the centre of the cursor moved beyond the perimeter of the home-target, and the end equated when the centre of the cursor moved within the perimeter of the end-target. Using these moments, the time-series position data was then extracted for each pre-test, post-test and imitation learning trial. The position data for each trial were processed using a low-pass 4th order autoregressive filter with an 8 Hz cut-off, and then differentiated using a 2-point central difference algorithm to obtain velocity and acceleration.

To quantify imitation, movement duration from the time-series data was extracted from each participant across all movement reproduction trials (pre-test, post-test, and imitation trials). From the movement duration data, an error score was calculated (*temporal constant error; CE*) which is a measure reflecting the average signed deviation (e.g., plus or minus) between a participant's movement time on *trial n* (e.g., 1900 ms) and the criterion timing goal that is 1700ms (e.g., a movement time

of 1900 ms would lead to +200ms, and a movement time of 1500 ms would lead to -200ms), and temporal variable error (VE) that reflects the variability in the participant's responses across a set number of trials (e.g., 10 trials, see the data analysis section below) around the average CE for the same 10 trials. To calculate movement duration, the start of a movement was defined as the moment the centre of the cursor moved beyond the perimeter of the home-position, whereas movement end equated to the moment the participant clicked the button on the stylus. Intra-participant mean CE and VE was calculated from all pre-test and post-test trials, as well as the first and last ten trials in imitation learning (early; late).

To quantify the execution of movement kinematics the analysis was focused on the x-axis data only (Hayes, Andrew, Elliott, Roberts, & Bennett, 2012; Hayes, Elliott, & Bennett, 2010; Hayes, Elliott, & Bennett, 2013; Hayes et al., 2014). Within the x-axis position data, the start and end of the movement (as defined above) was identified. A MATLAB routine extracted *percentage-time-to-peak-hand-velocity* (*tPHV*) from each trial. Intra-participant means were calculated from all pre-test and post-test trials, as well as the first and last ten trials in imitation learning (early; late). This kinematic dependent variable was chosen as it provides a discrete measure that accurately reflects whether participants execute the timing characteristics of the observed movement (Hayes et al., 2014).

Eye Movement Data:

To quantify eye movements during action-observation during the pre-test, observational practice, and imitation the analysis focused on the x-axis data taken from the left-eye. Synchronisation signals from the TTL interface were used to identify the start and end of stimulus presentation with the corresponding eye movement determined in relation to the stimulus onset for each trial. Saccades were

identified in the x-axis eye position data using the proprietary algorithm in the EyeLink software. The criterion for saccade identification was a velocity threshold of 30 deg/s, acceleration threshold of 8000 deg/s2, and a motion threshold of 0.15 deg. Saccades plus an additional five data points (equivalent to 20 ms) at the beginning and end of the identified saccade trajectory were then removed from the eye velocity trace. The removed data were replaced by a linear interpolation routine based on the smooth eye velocity before and after the saccade (Bennett & Barnes, 2003). The desaccaded smooth eye velocity was then low-pass filtered using a moving average zero-phase filter (40 ms window). To quantify how well the eye matched the velocity trajectory of the observed model, *percentage-time-to-peak-smooth-eye-velocity (tPSEV)* was extracted for each trial. Intra-participant means were calculated for the ten pre-test trials, the first 10 observational practice trials (early OP), the last ten observational practice trials (late OP), and the first and last ten imitation learning trials (early imitation; late imitation). The latter measure was analogous to that described above for the analysis of hand kinematics.

Data Analysis

Behavioural Data:

Changes in motor performance throughout the study were examined by analysing mean CE, VE and *tPHV*. To examine any changes as a function of observational practice, data were submitted to separate 2 group (autism; control) x 2 phase (pre-test; post-test) mixed ANOVA. To examine whether there was any change during the imitation task, data were submitted to separate 2 group (autism; control) x 2 phase (early; late) mixed ANOVA. Significant main and/or interaction effects were decomposed using Fisher LSD post-hoc procedure, with alpha set at $p < 0.05$ and partial eta squared (η_p^2) used to express the size of the effect.

Eye Movement Data:

Eye behaviour was investigated by examining *tPSEV* during the action-observation component of the pre-test, observational practice (early and late phases), and imitation (early and late phases) using a 2 group (*autism; control*) x 5 phase (pre-test, observational practice early, observational practice late, imitation early, imitation late) mixed ANOVA. Mauchly's Sphericity Test was used to test for a violation (i.e. $p < 0.05$) to sphericity across the 5 levels of the within factor. If violated, the degrees of freedom were adjusted using Greenhouse-Geisser. Significant main and/or interaction effects were decomposed using Fisher LSD post-hoc, with alpha set at $p < 0.05$. Partial eta squared (η_p^2) was used to express the size of the effect.

5.3 Results

Behavioural Data

Observational Practice:

Temporal constant error data are illustrated in *Figure 5.2.A*. Although ANOVA revealed no significant effects for the phase x group interaction [F (1, 38) = 1.69, $p > 0.05$, $\eta_p^2 = 0.087$], or the main effect for group [F (1, 38) = 0.85, $p > 0.05$, $\eta_p^2 = 0.022$], the phase [F (1, 38) = 12.41, $p < 0.01$, $\eta_p^2 = 0.246$] effect indicated that *temporal constant error* decreased by an average of 246.16 ms from pre-test to post-test. For information, the autism group improved accuracy by 80 % by decreasing CE from 421.21 ± 476.99 ms in the pre-test to 84.29 ± 567.46 ms in the post-test, and by 67 % for the control group from 230.49 ± 267.23 ms to 75.10 ± 233.67.

Temporal variable error data are illustrated in *Figure 5.2.B*. Although ANOVA revealed no significant effects for phase [F (1, 38) = 0.16, $p > 0.05$, η_p^2 =

0.004], or phase x group interaction [F (1, 38) = 0.33, $p > 0.05$, $\eta_p^2 = 0.009$], the main effect of group [F (1, 38) = 4.53, $p < 0.05$, $\eta_p^2 = 0.107$] indicated the autism group [pre-test: 293.58 ± 139.63 ms; post-test: 270.50 ± 162.38 ms] was on average 68.59 ms more variable than the control group [pre-test: 211.34 ± 103.74 ms; post-test: 215.56 ± 86.97 ms].

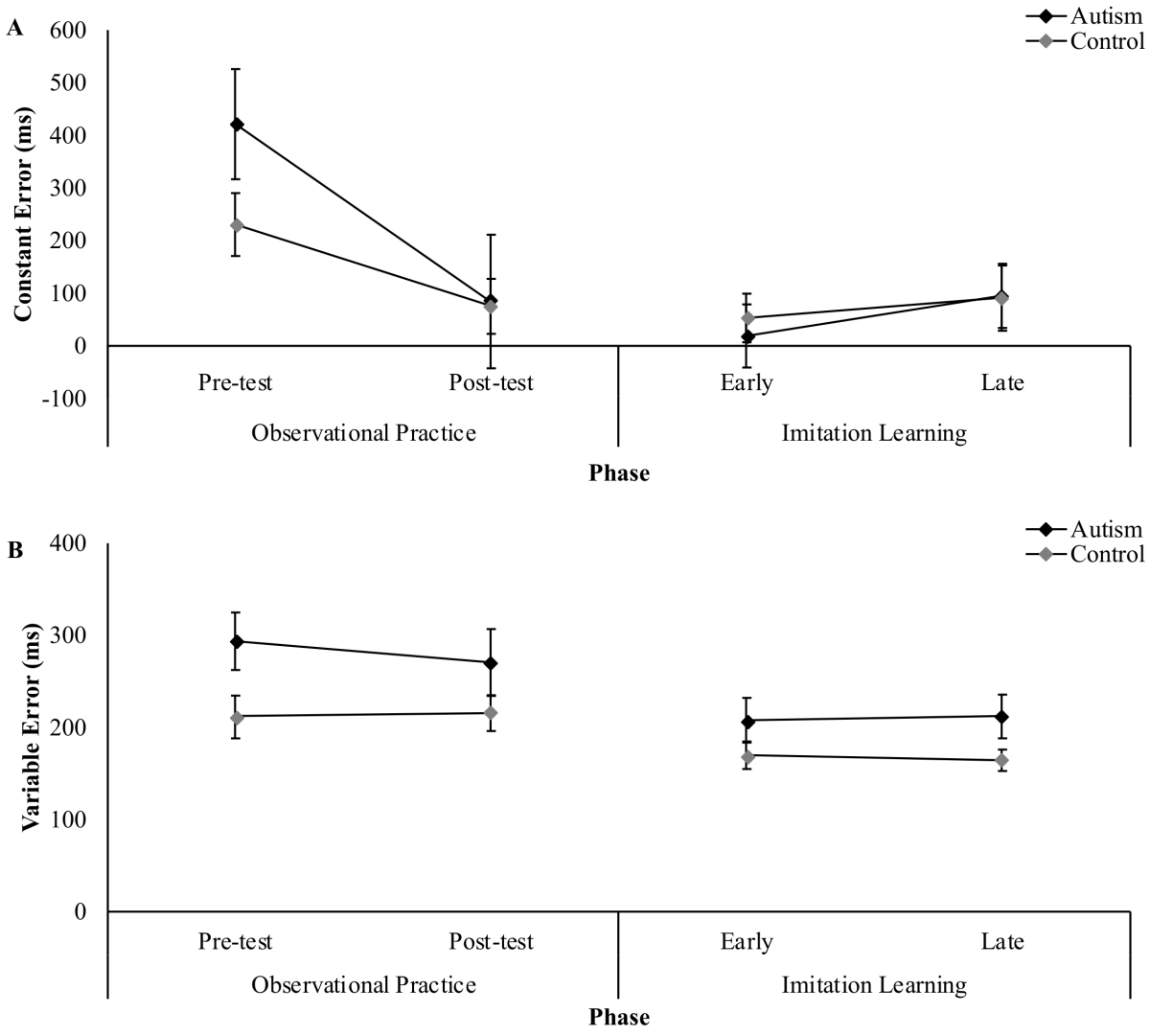

Figure 5.2: Mean temporal constant error (A) and mean temporal variable error (B) presented as a function of group and phase. Error bars represent standard error of the mean.

tPHV data are illustrated in *Figure 5.3.A*. Although there were no significant effects for the phase x group interaction [F (1, 38) = 0.59, $p > 0.05$, $\eta_p^2 = 0.015$], or main effect of group [F (1, 38) = 0.06, $p > 0.05$, $\eta_p^2 = 0.002$], the phase effects [F (1,

38) = 31.47, $p < 0.001$, $\eta_p^2 = 0.453$] revealed that *tPHV* decreased by an average of 11.6 units from pre-test to post-test and indicated that the peak occurred earlier in the movement trajectory in the post-test (see left-hand-side of *Figure 5.3.A*). For information, the autism group changed by 25% from 40.81 ± 9.19 in the pre-test to 30.80 ± 7.49 in the post-test, and the control group by 31% from 42.97 ± 8.32 in the pre-test to 29.78 ± 13.47 in the post-test.

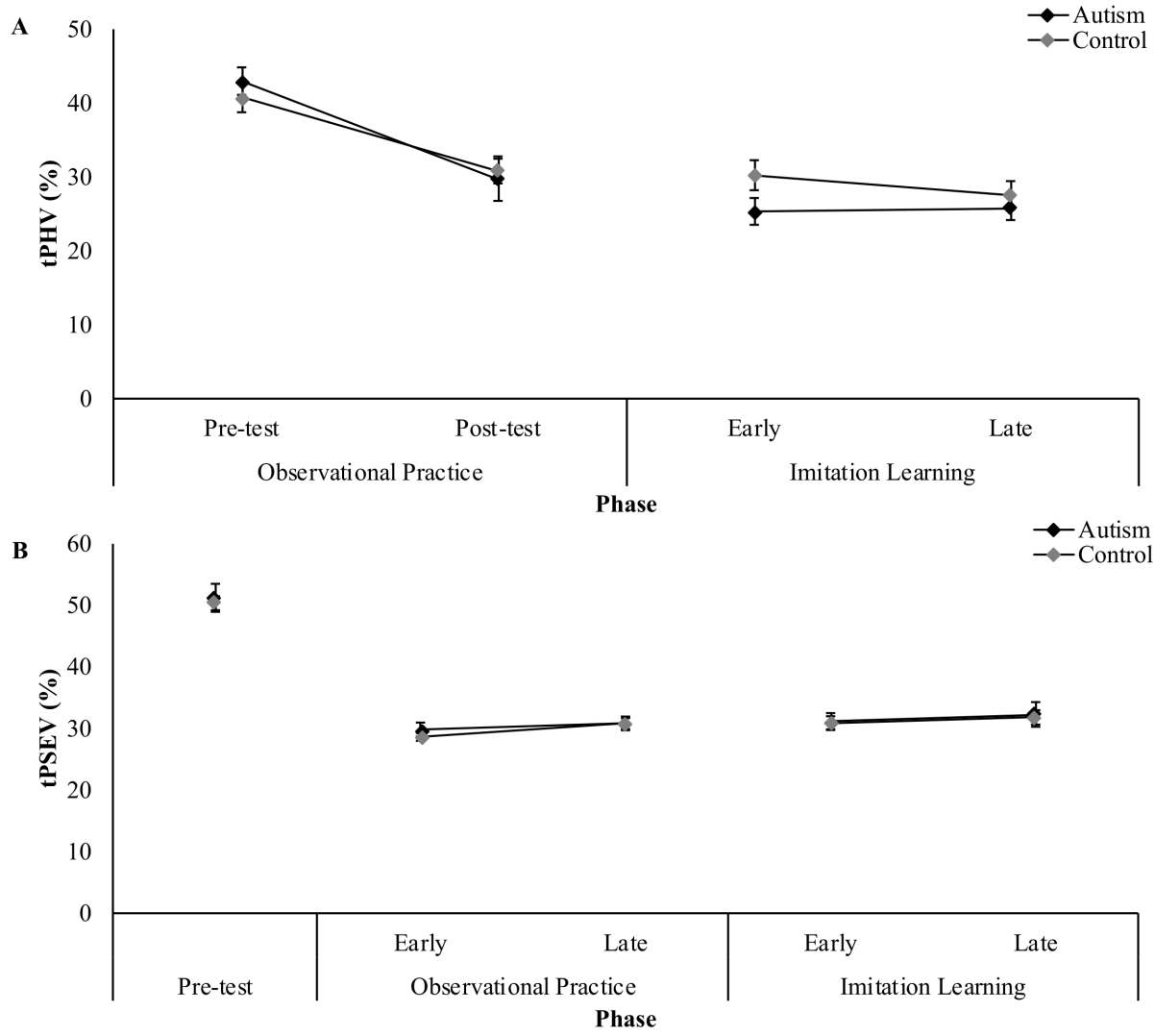

Figure 5.3: Mean percentage-time-to-peak-hand-velocity (A) and mean percentage-time-to-peak-smooth-eye-velocity (B) presented as a function of group and phase. Error bars represent standard error of the mean.

Imitation

For *temporal constant error*, ANOVA revealed no significant effects for phase [F (1, 38) = 3.39, $p > 0.05$, $\eta_p^2 = 0.082$], group [F (1, 38) = 0.04, $p > 0.05$, $\eta_p^2 = 0.001$], or phase x group interaction [F (1, 38) = 0.39, $p > 0.05$, $\eta_p^2 = 0.010$]. The mean data for the autism group in the early phase is 18.81 ± 268.16 ms and late phase is 95.03 ± 272.87 ms, and for control group the mean in the early phase is 53.01 ± 206.49 ms and the late phase is 90.72 ± 277.38 ms.

For *temporal variable error*, ANOVA revealed no significant effects for phase [F (1, 38) = 0.02, $p > 0.05$, $\eta_p^2 = 0.000$], group [F (1, 38) = 3.33, $p > 0.05$, $\eta_p^2 = 0.081$] or a phase x group interaction [F (1, 38) = 0.11, $p > 0.05$, $\eta_p^2 = 0.003$]. The mean data for the autism group in the early phase is 207.83 ± 108.60 ms and late phase is 211.90 ± 106.11 ms, and for control group the mean in the early phase is 168.82 ± 66.78 ms and the late phase is 164.35 ± 51.99 ms.

tPHV data are illustrated in *Figure 5.3.A*. Although there were no significant effects of phase [F (1, 38) = 2.28, $p > 0.05$, $\eta_p^2 = 0.057$], or group [F (1, 38) = 1.71, $p > 0.05$, $\eta_p^2 = 0.043$], the significant phase x group interaction [F (1, 38) = 4.73, $p < 0.05$, $\eta_p^2 = 0.111$] indicated no significant change in the control group from early (25.34 ± 8.10) to late (25.83 ± 8.56), whereas the autism group adapted ($p < 0.05$) movement reproduction by 9 % so that peak velocity occurred earlier in the late phase (27.53 ± 8.56) compared to the early phase (30.34 ± 9.08).

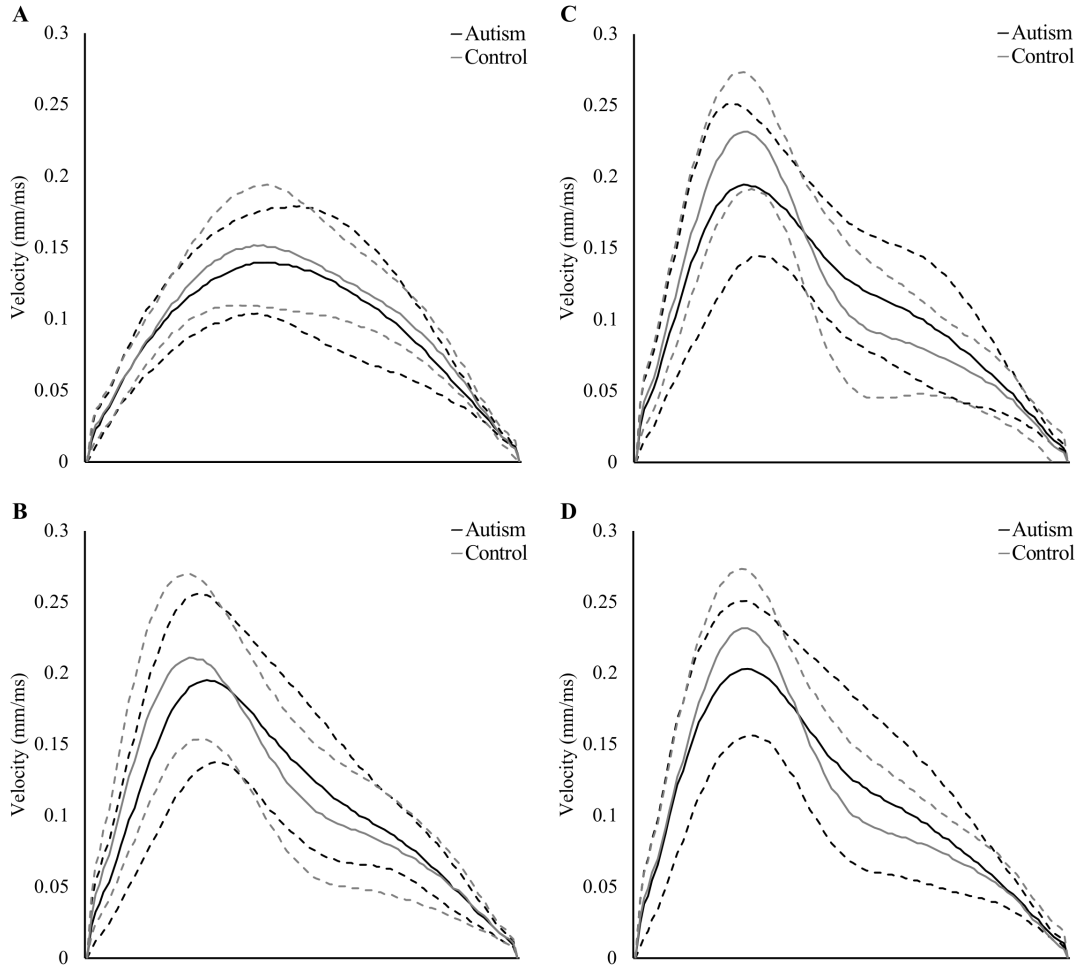

Figure 5.4: Mean velocity traces for the autism (black traces) and control (grey traces) groups during the pre-test (A) and post-test (B) of the OPp and during the early (C) and late (D) phases of the ILp. Dashed lines represent the standard deviation of the mean

Eye Movement Data:

ANOVA revealed no significant main effect of group [F (1, 29) = 0.26, p > 0.05, η_p^2 = 0.009] or phase x group interaction [F (2.45, 70.94) = 2.58, p > 0.05, η_p^2 = 0.003], but the effect of phase was significant [F (2.45, 70.94) = 4002.38, p < 0.05, η_p^2 = 0.813]. As illustrated in *Figure 5.3.B*, the post hoc analysis indicated that *tPSEV* significantly (p > 0.05) decreased by 41% from 50.71 ± 6.34 in the pre-test to 29.83± 4.08 in the early phase of observational practice. There were no significant

differences between the early phase of observational practice and the other three phases (*ps* > 0.05).

5.4 Discussion

The contribution of sensorimotor integration during imitation of atypical biological kinematics in autism was examined in a repeated-measures design study that utilised an 'observational practice protocol (OPp)' followed by an 'imitation learning protocol (ILp)'. The OPp was selected because unlike imitation, that requires trial-to-trial observation-execution, this type of observational learning protocol controls the involvement of the peripheral motor system thus limiting the contribution of sensorimotor integration (i.e., no explicit efference or reafference) during learning. Prior to observational practice, the pre-test was employed to establish comparable baseline motor behaviours for both groups based on imitating a model that displayed a *typical* goal-directed velocity profile (peak occurred at 44% of the movement trajectory). Consistent with data from other imitation studies that displayed similar models performing *typical* goal-directed movements (Andrew, Bennett, Elliott, & Hayes, 2016; Hayes et al., 2016), the *tPHV* results indicated that both groups reproduced movements where peak velocity occurred towards the mid-point of the movement trajectory at baseline (autism = 41%; control = 43%). These movement effects indicate that both groups executed similar *typical* goal-directed velocity profiles following the short period of baseline imitation.

The error data from the OPp indicated that the autistic (80% change) and control (67% change) groups significantly improved timing performance by decreasing temporal constant error (by 246 ms) from pre-test to post-test. The movements performed in the post-test were based on processes associated with memory recall because no model was provided to form the basis of visual input for

motor execution. Therefore, in order to plan the motor commands required for motor execution participants most likely formed an inverse model from an acquired internal action model represented during observational practice (Desmurget & Grafton, 2000; Wolpert & Flanagan, 2010). The learning effects replicate findings that showed neurotypical controls acquire motor timing via observational practice (Blandin, Lhuisset, & Proteau, 1999; Hayes, Timmis, & Bennett, 2009; Vogt, 1995), but importantly the data from the autism group are the first to demonstrate this type of sensorimotor learning is operational in autism. Although motor timing performance improved, the main effect of group for temporal variable error indicated motor execution was less consistent in the autism group during imitation (pre-test) and motor recall (post-test). This finding replicates data indicating autism groups showed greater motor timing variability when executing movements using a similar experimental apparatus during imitation learning (Hayes et al., 2016) and sensorimotor learning (Hayes et al., 2018). Moreover, the specificity in motor variability adds to the growing consensus that sensorimotor differences (e.g., sensorimotor noise; integration; planning) play a significant modulatory role in shaping behaviour in autism (Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Gowen & Hamilton, 2013; Leary & Hill, 1996).

In addition to acquiring motor timing during observational practice, the *tPHV* data indicate that both groups executed movements in the post-test where peak velocity occurred significantly earlier in the movement trajectory (autism = 31%; control = 30%) compared to baseline (autism = 41%; control = 43%). The change of 10 units of *tPHV* for the autism group is important because the executed movement in the post-test was similar to the *atypical* model, and consistent with data from neurotypical controls that represented atypical biological kinematics via observational practice (Hayes et al., 2014). Because the *atypical* model was novel,

and therefore could not be reproduced by rescaling a pre-existing movement based on higher-order semantic processes (Rumiati et al., 2005), the representation of biological kinematics mostly likely occurred within an action-observation learning mechanism containing lower-level processes linking visual and motor representations (Catmur & Heyes, 2011; Catmur, Walsh, & Heyes, 2007; R. Cook, Bird, Catmur, Press, & Heyes, 2014). The fact that the learning of *atypical* biological kinematics occurred when the peripheral motor system was not task specifically engaged during observational practice, and therefore the requirement to integrate visual input with motor output on each trial was controlled, supports the suggestion (Hayes et al., 2016; Mostofsky & Ewen, 2011; Nebel et al., 2016) that imitation difficulties in autism are underpinned by differences in sensorimotor integration.

The results from the imitation learning protocol provide support for this suggestion as the two groups showed differential transfer effects when engaged in trial-to-trial imitation of the *atypical* biological kinematics. The significant interaction effect for the *tPHV* data indicated no significant adaptation across trials for the control group with peak velocity occurring at 25% of the trajectory in the early phase, and 26% in the late phase. Although not quantified statistically, the data showed that *tPHV* changed from 30% in the post-test, to 25% in the early phase indicating an immediate performance improvement. This behavioural effect was not shown by autism group, where *tPHV* was 30% in the early-phase (similar to the post-test value of 31%) and 28% in the late-phase. Although the absolute change in units is small, the degree of change was significant indicating that the autism adapted imitation performance across trials resulting in performance being similar to the control group. Therefore, and compared to the control group, these data suggest that the autistic participants required a greater number of trials to effectively integrate visual input with motor output.

Although there seems to be some differences in the efficacy of sensorimotor integration, the analysis of smooth pursuit data indicated that both groups performed similar eye movements when scaling the eye to attend to the *typical* (pre-test) and *atypical* (observational practice; imitation learning) models. Although, altered visual attention in autism has previously been suggested to impact imitation accuracy (Gonsiorowski, Williamson, & Robins, 2016; Vivanti & Dissanayake, 2014; Vivanti et al., 2008; Wild et al., 2012), the fact that eye behaviour was accurately scaled to the different models suggests that velocity information (Bennett & Barnes, 2004; Krauzlis & Lisberger, 1994) from the non-human model was accessible for visual input during action-observation. Consequently, the potential difference in the integration of reafferent information in the imitation learning phase for the autism group appears to be specific to integrating visual input with motor output rather than overt visual attention directed to the model.

These findings therefore suggest that the processing of visual information during action-observation, and via eye movements, is operational in autism. Therefore, the evidence points towards an integration difficulty when autistic participants combine visual information with proprioceptive reafference that might impact the efficacy of forming internal action models during imitation (Hayes et al., 2016; Hobson & Lee, 1999; Rogers et al., 1996; Stewart et al., 2013; Vanvuchelen et al., 2007; Wild et al., 2012). In addition to the aforementioned behavioural data, altered neural connectivity during action model formation has been suggested (Mostofsky & Ewen, 2011) to underpin imitation differences in autism where participants prioritise proprioceptive feedback over visual feedback (Haswell et al., 2009; Izawa et al., 2012; Marko et al., 2015). Importantly, however, the findings from the observational practice protocol indicate that in the absence of

proprioception autistic participants successfully encode biological motion information to form an internal action model.

In conclusion, autistic participants reproduced novel *atypical* biological kinematics following a period of observational practice. This demonstrates that lower-level sensorimotor processes, linking perception and action, are operational in autism and facilitate the encoding of visual information into an internal action model. Although the perception-action system is operational, imitation differences occur when integrating visual input with motor output. Therefore, imitation difficulties in autism appear to be underpinned by differences in sensorimotor integration whereby less effective processing of reafferent sensorimotor information impacts the efficacy of developing internal action models.

6 Chapter Six: Epilogue

The programme of work presented in this thesis examined the central question of sensorimotor integration in autism spectrum disorders across four independent experimental chapters. Within this epilogue the key findings will be summarised and critically evaluated with regards to the current literature. Theoretical implications will be considered and then future directions and research applications for the field autism spectrum disorders will be discussed.

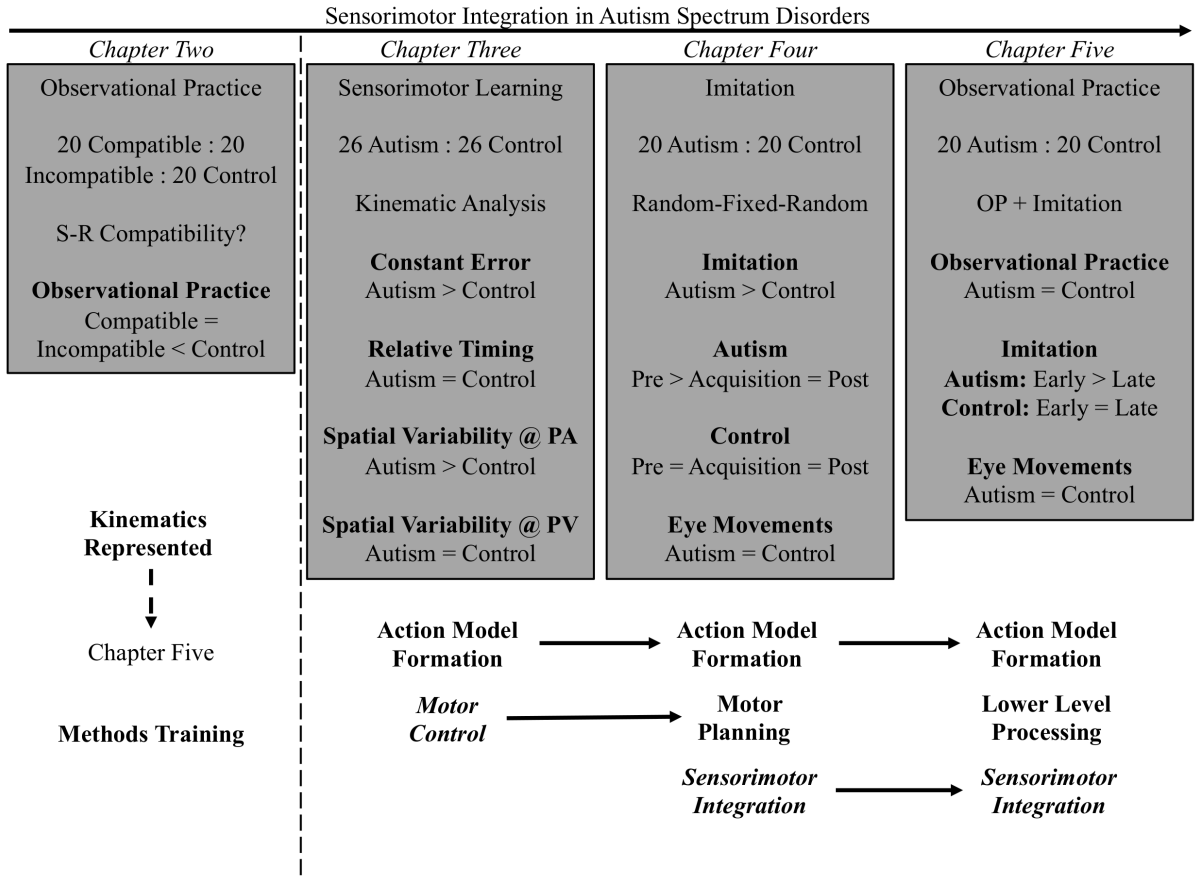

Figure 6.1: Overview of the experimental design and key findings of each chapter.

6.1 General Summary

Within the current programme of work autistic participants were matched (IQ, age, gender) with control participants across three experimental chapters (chapters three to five) to examine sensorimotor integration within contexts of motor learning, imitation and observational practice. An additional control experiment

(chapter two), which examined observational practice, was conducted in order to determine suitable data collection and analysis techniques. Overall, through the use of different methodologies and analysis techniques, the experiments conducted within these chapters have expanded the understanding of sensorimotor processing in autism. Specific details of the findings of these experiments are reported in the chapter summaries below.

Chapter Two

The aim of chapter two was to investigate the effect of S-R compatibility on the representation of atypical biological kinematics during observational practice. That is, whether the spatial position of peak velocity is encoded during action-observation (Hommel & Lippa, 1995), or the atypical biological motion kinematics (Hayes, Roberts, Elliott, & Bennett, 2014). The atypical stimulus used had movement time of 1700 ms, with a peak velocity of 0.33 mm/ms, which occurred at 18 % of movement duration (see *Figure 2.1.B*). The presentation of atypical kinematics was fundamental for the understanding of how lower-level sensorimotor processes contribute to observational practice. For example, if a model was used that displayed a typical, bell-shaped velocity profile, then the resulting motor execution following imitation could be associated with rescaling a pre-existing motor representation via top-down processes (Rumiati et al., 2005), or via lower-level processing of atypical kinematics. Therefore, a model displaying novel atypical kinematics is suggested to be optimal to investigating the contribution of lower-level processes during imitation and observational practice because it requires the sensorimotor system to be configured based on the biological kinematics in order for a novel movement to be reproduced during imitation. Before the study commenced, participants were randomly assigned to a compatible group who observed the

atypical move rightwards, an incompatible group who observed the atypical model move leftwards, or a control group who did not engage in observational practice. It was hypothesised that the compatible group would perform more accurately than the incompatible group if the reproduction of atypical kinematics during imitation was underpinned by higher-order processes associated with S-R compatibility. Whereas both groups would be comparable if reproduction is underpinned by lower-level sensorimotor processes.

Examination of post-test performances for *percentage-time-to-peak-hand-velocity* (tPHV) revealed that the compatible (28 %) and the incompatible (31 %) groups demonstrated comparable accuracy when reproducing atypical kinematics following observational practice. Moreover, both were significantly more accurate than the control group (40%). Bayesian statistics also indicated insufficient evidence to accept the experimental hypothesis that the compatible and incompatible groups would differ. This study therefore isolated the reproduction of atypical kinematics following observational practice to lower-level processes linking visual and motor representations (Catmur & Heyes, 2011; Catmur, Walsh, & Heyes, 2007).

Chapter Three

The aim of chapter three was to examine motor learning and sensorimotor control processes in autism. This chapter investigated the formation of an internal action model over a thirty trial acquisition period where participants practised a three-segment visuomotor sequence timing task (VSTT) with a movement time of 1700 ms with resultant knowledge of results was provided on every trial. This was then followed a retention, where feedback in the form of knowledge of results was removed, in order to assess learning. The relative timing structure of the three-segment movement was also across all trials, as well as the efficacy of sensorimotor

control processes related to motor execution and motor planning in autism. Variability in the spatial position of peak acceleration and peak velocity was extracted for each movement segment to study how both feedforward and feedback control processes (Elliott et al., 2010) impact motor execution in autism.

The findings showed that both groups became significantly more accurate performing the VSTT as evidenced by reductions in *temporal constant error* (CE) from the early phase (Autism: 1234.83 ± 667.10 ms; Control: 808.54 ± 384.82 ms) to the late phase (Autism: 449.07 ± 348.65 ms; Control: 279.49 ± 237.43 ms) of the acquisition period. Similarly, both groups also became more consistent as a function of the acquisition phase, reducing *temporal variable error* (VE) between the early phase (Autism: 498.29 ± 279.58 ms; Control: 497.32 ± 350.22 ms) and late phase (Autism: 229.79 ± 108.10 ms; Control: 150.82 ± 97.69 ms). Although the autism group demonstrated sensorimotor adaptation as a function of trial and error learning, they were on average 298 ms less accurate than the control group during the acquisition phase. Significant group effects were also observed in the retention test where the autism group (594.05 ± 437.57 ms) were 304 ms less accurate than the control group (290.35 ± 206.48ms), as well as 90 ms more variable (Autism: 380.21 ± 107.35 ms; Control: 289.91 ± 79.98 ms). Importantly the analysis of *relative timing*, which quantified how the sensorimotor system is constrained by the spatial-temporal constraints of the task, indicated that the autism group executed a comparable timing pattern (Segment 1: 30 ± 3 %; Segment 2: 29 ± 3 %; Segment 3: 41 ± 4 %) to the control group (Segment 1: 30 ± 2 %; Segment 2: 30 ± 2 %; Segment 3: 40 ± 3 %). Taken together (*CE; VE; relative timing*), these findings indicate that the formation of an internal action model during the acquisition of a novel sensorimotor timing task is operational in autism (Gidley Larson, Bastian, Donchin, Shadmehr, & Mostofsky, 2008; Hayes et al., 2018), and that the sensorimotor

systems of autism and control participants were constrained in a similar manner by the spatio-temporal characteristics of the task. However, analysis of segment three did show that autistic participants did spend proportionally more time in this final segment. Likewise, despite the positive learning effects for the autistic participants in the terms of action model formation, *temporal constant error* indicated greater scores in both acquisition and retention for the autism group and *temporal variable error* was greater in retention. Therefore, although the trial-to-trial processing of sensorimotor efferent and afferent feedback, plus knowledge of results, led to sensorimotor adaptation in the autism group, motor execution following a limited practice period was still less accurate and more variable suggesting that specificity effects may constrain the nature of overt motor behaviour.

A potential mechanism that could contribute to these differences in motor execution is the underlying sensorimotor feedforward and feedback control processes (Desmurget & Grafton, 2000; Wolpert & Kawato, 1998) . To examine these processes in relation to a theoretical model forwarded by Elliott and colleagues (2010; *see Figure 1.2*) measures of spatial variability at peak acceleration (*sdPA*) and peak velocity (*sdPV*) were quantified. During the acquisition period, the autism group (10.27 ± 2.51 mm) were 1.49 mm more variable than the control group (8.78 ± 2.36 mm) at peak acceleration. There were also significant differences between the groups (Autism: 9.32 ± 3.70 mm; Control: 7.20 ± 2.36 mm) for *sdPA* during the retention test. Importantly, however, these significant differences were not present upon reaching peak velocity in the movement trajectory in the acquisition phase and retention test. For example, in the retention test the difference in *sdPV* between the autism group (11.95 ± 5.33 mm) and the control group (12.31 ± 6.01 mm) was 0.36 mm. These effects provide an insight into the underlying sensorimotor control differences that might contribute to the general movement differences observed in

constant and *temporal variable error* for the autism group. Specifically, the temporal period between movement initiation and peak acceleration is known to be associated with sensorimotor planning and feedforward control (Elliott et al., 2010), where adjustments to the initial movement are made based on the comparison of the expected sensory consequences (e.g., efference copy) and the actual movement (e.g., reafference). The implication is that the difference observed between the autism and control groups at this stage of the movement could be associated with motor planning issues in autism that are related to the specification of muscular forces (Glazebrook, Elliott, & Lyons, 2006; Rinehart, Bradshaw, Brereton, & Tonge, 2001). In addition to a planning contribution, the increased variability could be related to the efficacy of the feedforward processes (Elliott et al., 2010; Glazebrook et al., 2006; Mosconi et al., 2015) that compare the actual, to expected, sensorimotor information (further discussion of these processes is present in section 6.3). However, the fact that the variability difference was between the groups was significantly reduced by peak velocity indicates that the later aspects of sensorimotor control (Saunders & Knill, 2005) that are based on processing available afferent information (visual and proprioception) are operational in autism.

Chapter Four

The aim of chapter of four was to investigate sensorimotor planning and integration in autism during an imitation learning protocol designed to facilitate the encoding of atypical biological kinematics. A specific difficulty in the imitation of lower-level biological kinematic properties has previously been observed in autism (DeMyer et al., 1972; Hayes, Andrew, Elliott, Gowen, & Bennett, 2016; R. P. Hobson & Lee, 1999; Rogers, Bennetto, McEvoy, & Pennington, 1996; Stewart, McIntosh, & Williams, 2013; Wild, Poliakoff, Jerrison, & Gowen, 2012), which has

been associated with differences in sensorimotor planning and integration (Hayes et al., 2016) and visual attention (Wild et al., 2012). Whilst previous studies have used randomised, unpredictable trial orders (Hayes et al., 2016; Stewart et al., 2013; Wild et al., 2012), during the imitation acquisition period in chapter four the atypical model was presented in a predictable fixed-trial order for 30 trials. This fixed-trial order therefore creates an imitation context where the observed sensorimotor information from trial *n* (i.e., atypical model) is the same as trial *n+1* (i.e., atypical model). Moreover, and to facilitate sensorimotor integration across trials, the fixed-trial order enables learners to compare and process the expected and actual sensorimotor consequences from trial *n* in order to input into the sensorimotor planning operations for trial *n+1* (Elliott, Helsen, & Chua, 2001; Wolpert, Diedrichsen, & Flanagan, 2011). To examine imitation accuracy, *tPHV* was extracted from each imitation trial, to assess how accurately participants reproduced the velocity profile of the observed movement. To examine visual attention eye movements were also recorded throughout all phases of the study. The fixed trial-order was therefore used to facilitate sensorimotor integration and encoding of the atypical model in the autism group. If this was the case, the acquisition period was expected to result in more accurate imitation (i.e., *tPHV* closer to 18 %) of the atypical model than in the pre-test (random trial-order), with the autistic participants also expected to show significant increases in imitation accuracy across the acquisition period itself. Moreover, if imitation learning occurred as result, and the successful imitation of atypical biological kinematics in autism is related to sensorimotor integration and the formation of a new internal action model, *tPHV* was not expected to change when returning to a random trial-order in the post-test. Whereas, if imitation differences previously shown in experiments using random trial orders (Hayes et al., 2016) are related to motor planning issues in autism

(Hughes, 1996) which are increased by the unpredictable nature of random trial orders, then imitation accuracy was expected to decrease in post-test compared to the acquisition phase.

In general, although the control group imitated the observed kinematic properties of both models more accurately than the autism group, both groups successfully modulated imitation behaviour in relation to the atypical (Autism: 28.46 ± 8.96; Control: 20.99 ± 7.67) and typical (Autism: 36.76 ± 9.88; Control: 34.52 ± 9.29) model. In addition, neither group changed imitation behaviour across the imitation phase when reproducing the typical model. Similar findings were found for the control group with regards to the atypical model. As expected, however, the use of a fixed trial-order that was designed facilitate sensorimotor integration and encoding of the atypical model (Elliott et al., 2001; Wolpert et al., 2011) led to significant changes in imitation accuracy for the autism group. Firstly, the autism group showed a significant increase in imitation accuracy (%Δ = 17) during acquisition (26.68 ± 9.03) compared to the pre-test (32.25 ± 8.36), and importantly also showed increases in imitation accuracy across the acquisition phase (%Δ = 9). Secondly, when returning to a random trial-order in the post-test (28.10 ± 9.68), the autism group showed no significant change (%Δ = 7) from the late stage of acquisition (26.17 ± 8.32). Finally, an overall effect of imitation learning was present with imitation accuracy increasing (%Δ = 13) from the pre-test to post-test. Importantly, the above findings for imitation were not accompanied by any group differences in eye behaviour. Both groups successfully modulated their *percentage-time-to-peak-smooth-eye-velocity* (tPSEV) to represent the profile of the atypical model (Autism: 31.67 ± 6.33; Control: 30.37 ± 4.03) and the typical model (Autism: 50.55 ± 7.55; Control: 52.25 ± 5.03) regardless of whether these models were presented in a fixed or randomised trial order. Together these findings therefore

indicate that imitation differences previously reported in autism (DeMyer et al., 1972; Hayes et al., 2016; R. P. Hobson & Lee, 1999; Rogers et al., 1996; Stewart et al., 2013; Wild et al., 2012) are unlikely to be specifically related to issues in visual attention (Wild et al., 2012), but rather underpinned by specific processing atypicalities related to sensorimotor integration during the representation of biological motion

Chapter Five

The first aim of chapter five was to investigate whether individuals with autism could successfully reproduce atypical biological kinematics following an observational practice period in which they repeatedly observed a model without actively engaging the peripheral motor system (Bird & Heyes, 2005; Bird, Osman, Saggerson, & Heyes, 2005; Osman, Bird, & Heyes, 2005). The second aim of chapter five was to examine sensorimotor integration when updating a pre-existing internal action model which had been developed in the absence of proprioceptive feedback (i.e., during observation practice). This involved an imitation learning protocol (i.e., thirty consecutive imitation trials of the atypical model) administered immediately after the post-test. Finally, to confirm the location of overt visual attention, eye movements were recorded throughout both the observational practice and imitation learning protocol.

As a function of observational practice, the autism and control groups both showed significant increases (autism: $\%\Delta = 80$; control: $\%\Delta = 67$) in timing accuracy as shown by a reduction in temporal constant error from the pre-test (autism: 421.21 ± 476.99 mm; control: 230.49 ± 267.23 ms) to post-test (autism: 84.29 ± 567.46 ms; control: 75.10 ± 233.67 ms). However, the autism group (pre-test: 293.58 ± 139.63 ms; post-test: 270.50 ± 162.38 ms) was significantly more

variable in motor timing than the control group (pre-test: 211.34 ± 103.74 ms; post-test: 215.56 ± 86.97 ms). This finding indicates that the temporal characteristics of the observed movement (total movement time = 1700 ms) were represented by both groups following a period of observational practice that isolated the active contribution of peripheral motor system. In addition to the timing accuracy and variability effects, both groups imitated a *tPHV* that was significantly lower in the post-test (autism: 30.80 ± 7.49; control: 29.78 ± 13.47), compared to the pre-test (autism: 40.81 ± 9.19; control: 42.97 ± 8.32). This change across practice demonstrated that both groups showed comparable imitation behaviour (autism: %Δ = 25; control: %Δ = 31) following observational practice. Therefore, the fact that both groups produced *tPHV* values that were similar the atypical model indicates the internal action model formed by both groups was based on representing the observed lower-level biological motion properties of the atypical model. These learning effects for both groups are most likely underpinned by an operational common-coding system linking perception and action (Brass & Heyes, 2005; Jeannerod, 1994; Prinz, 1997; for further discussion please see section 6.2).

When participants were transferred to the imitation learning protocol neither the autism (early: 18.81 ± 268.16 ms; late: 95.03 ± 272.87 ms), or the control (early: 53.01 ± 206.49 ms; late: 90.72 ± 277.38 ms) group showed any further changes in timing accuracy. The autism (early: 207.83 ± 108.60 ms; late: 211.90 ± 106.11 ms) and control (early: 168.82 ± 66.78 ms; late: 164.35 ± 51.99 ms) groups also showed no further changes in variability. Furthermore, the significant difference in temporal variable error that was present in observational practice protocol between the autism and control groups was no longer present. In relation to how accurately participants successfully reproduced the lower-level kinematic properties, the control group showed no adaptation in *tPHV* (%Δ = 2) during the imitation learning protocol.

Whereas, the autism group's imitation behaviour did adapt (%Δ = 9) from the early (30.24 ± 9.09) to late (27.53 ± 8.56) phase of imitation learning. It was however of interest that the control group were immediately more accurate in their reproduction of the atypical kinematic profile when transferred to the imitation learning protocol, whereas the autism group required a greater number of trials to be similarly accurate given that both groups post-test performance was similar. These findings therefore provide further evidence of functional sensorimotor processes coupling perception and action in autism (Nackaerts et al., 2012), but that differences in sensorimotor integration do impact the continued development of internal action models in autism secti. With regards to the eye movement analysis, both groups attended to the stimuli in a similar way throughout the experiment, with no differences in their *tPSEV* present during any phase.

When viewed in isolation, each study in the current thesis contributes to the current understanding of autism in relation to sensorimotor learning, imitation, and observational practice. Importantly, two key themes emerge that will be discussed and appraised in relation to the current literature: (1) sensorimotor processing and (2) sensorimotor integration.

6.2 Implications for sensorimotor processing in autism spectrum disorders

Processing and encoding of biological kinematics during observation

Before the lower-level processing of biological motion is discussed in relation to imitation in autism, it is important to reiterate the use of an *atypical* model that permitted imitation to be quantified according to the timing and magnitude of velocity. This experimental manipulation ensured that participants were not able to merely recruit (from memory) and rescale an existing sensorimotor representation

associated with a typical aiming movement to solve the goal of imitating the novel *atypical* model (Buccino et al., 2004; Carmo, Rumiati, Siugzdaite, & Brambilla, 2013; Rumiati et al., 2005). Instead, because the *atypical* biological motion profile is unlikely to be represented in the participant's sensorimotor repertoire (Hayes et al., 2014), imitation required the *atypical* velocity profile to be learned via observation, encoding and execution. Data from Chapter 2 confirmed that typically developed participants processed and imitated the novel *atypical* model following observational practice, with the *compatible group* (29%) and *incompatible group* (31%) reproducing *tPHV* that were significantly different to the *control group* (40%), but comparable to the observed *atypical* model (18%). More importantly, because the constraints associated with stimulus-response compatibility were controlled during observational practice, the results indicate imitation learning in control participants was underpinned by processes that encoded the observed biological kinematics via lower-level visuomotor processes (Brass & Heyes, 2005; Jeannerod, 1994; Prinz, 1997), as opposed to top-down processes associated with encoding the spatial position of the atypical kinematic landmark (Hommel & Lippa, 1995).

As stated, the initial requirement when imitating a novel movement is the processing and perception of biological motion. This enables an action end-goal (i.e., pressing a light switch) and the lower-level kinematic properties (i.e., velocity of the limb) to be encoded via complimentary processing streams (Hamilton, 2014; Iacoboni et al., 2001; Iacoboni et al., 2005; Iacoboni et al., 1999). Specifically, the observed biological visual information is processed within a visuomotor network (e.g., action-observation network, Iacoboni et al., 2001; Iacoboni et al., 2005; Iacoboni et al., 1999) containing the middle temporal gyrus (Rizzolatti et al., 1996) and the superior temporal sulcus (Allison, Puce, & McCarthy, 2000), plus inferior frontal gyrus (Kilner, Neal, Weiskopf, Friston, & Frith, 2009) where he lower-level

kinematic properties are encoded, and the inferior parietal lobule (Hamilton & Grafton, 2006) where an action end-goal is processed. Although sensorimotor processing of biological motion within the action-observation network is operational during imitation learning in neurotypical participants (Buccino et al., 2004; Vogt et al., 2007), it has been suggested that parts of this imitation processing system are different in autism (Williams, Whiten, Suddendorf, & Perrett, 2001). Evidence for differential activity in autism has been demonstrated using combined behavioural and neuroimaging techniques (Bernier, Dawson, Webb, & Murias, 2007; Dapretto et al., 2006; Oberman et al., 2005; Théoret et al., 2005; Williams et al., 2006). For example, the first evidence of differences in neural activity within the action-observation network was based on a study that examined processes underlying the imitation of emotional face expressions. Compared to control children, autistic children exhibited reliably lower neural activation in the frontal area (i.e., pars opercularis) of the action-observation network during both observation and imitation conditions (Dapretto et al., 2006). Still, despite the difference in neural activity, both groups of children successfully imitated the observed facial gestures. Of particular interest to the present thesis, is the fact that differential behavioural and neural effects have also been reported in a fMRI study (Williams et al., 2006) that examined neural activity during a motor imitation task (i.e., finger imitation task similar to the classic automatic imitation protocols; i.e., Iacoboni et al., 1999). As before, both groups successfully imitated the observed finger movement but there was a difference in neural activation across a broad action-observation network, and in particular the anterior parietal region. Interestingly, the authors suggested the autistic children imitated the observed visual stimuli by engaging an alternative visuomotor learning mechanism that reconfigured previously learnt (similar) motor actions. The implication is that although there is some evidence of differential neural

processing within the action-observation network during imitation in autism, this is unlikely to be the principle mechanism that underpins the differences reported in the efficacy of imitation (Bird, Leighton, Press, & Heyes, 2007; Hamilton, 2014; Hamilton, Brindley, & Frith, 2007; Sowden, Koehne, Catmur, Dziobek, & Bird, 2016).

Moreover, it is clear from eye-tracking (Vivanti et al., 2011), EEG (Fan, Decety, Yang, Liu, & Cheng, 2010), fMRI (L. E. Marsh & Hamilton, 2011) and automatic imitation (Bird et al., 2007; Edey et al., 2016; Hamilton et al., 2007; Press, Richardson, & Bird, 2010; Schulte-Rüther et al., 2017; Sowden et al., 2016; Spengler, Bird, & Brass, 2010) studies that the neural processes underlying overt imitation behaviour are operational in autism. Specifically, and consistent with the adaptation findings reported in Chapter 4 (imitation learning) and 5 (observational practice) of this thesis, the behavioural findings from studies examining automatic imitation [which is a form of imitation requiring fewer non-specific imitation (e.g., executive function; attention; sensorimotor learning) mechanisms than those recruited during voluntary imitation] in autism have shown operational perception-action processing of biological (Press et al., 2010; Sowden et al., 2016) and non-biological (Bird et al., 2007) motion. For example, Bird et al. (2007) reported that autistic individuals showed functional automatic imitation of robotic actions, and greater automatic imitation of human actions, similar to those of control participants. This greater imitation effect in autistic and control participants suggests a preferential bias towards biological motion based on more exposure to this type of motion information, and therefore sensorimotor experience of human stimuli (Press, 2011; Press et al., 2012). Moreover, the functional automatic imitation effects indicate that the visuomotor processes within the action-observation network (Heyes,

2011), which translate observed motion into executed actions, are operational in autism.

Indeed, and extending upon the aforementioned work that showed intact automatic imitation in autism (e.g., Bird et al., 2007) was underpinned by a visuomotor system that develops through sensorimotor experience/learning (Catmur et al., 2007; Cavallo, Heyes, Becchio, Bird, & Catmur, 2013; Press, Gillmeister, & Heyes, 2007), the observational practice findings reported in Chapter five of the current thesis showed for the first time that autistic individuals demonstrated intact sensorimotor learning of *atypical* biological kinematics via action-observation. Following a short period of observational practice (30 trials) the autism and control groups adapted baseline (pre-test) sensorimotor behaviour from a *typical* goal-directed velocity profile (Autism: 40.81 ± 9.19; Control: 42.97 ± 8.32) to an *atypical* velocity profile in the post-test (Autism: 30.80 ± 7.49; Control: 29.78 ± 13.47). The important aspect of this type of learning is that the encoding of *atypical* biological kinematics occurred without the active contribution of the peripheral motor system (Berger & Hadley, 1975; Berger, Irwin, & Frommer, 1970) because at no point during practice was the observed biological motion physically executed/imitated. Therefore, by controlling the modulatory impact that associated general non-specific sensorimotor learning processes have on voluntary imitation in autism (Hayes et al., 2016) the present observational practice data (chapter 5) indicates the visuomotor resonance system that underpins observational practice/learning (Cross, Kraemer, Hamilton, Kelley, & Grafton, 2009; Higuchi, Holle, Roberts, Eickhoff, & Vogt, 2012; Stefan et al., 2005) is operational in autism.

The positive observational practice effects (i.e., learning of *atypical* biological kinematics) reported in Chapter 5 offer some important insights into the sensorimotor processing operations that are engaged during voluntary imitation in

autism. For example, the use of *atypical* biological kinematics of a novel action would have minimised learning via top-down semantic processes associated with retrieving a pre-existing sensorimotor representation from memory (Rumiati et al., 2005). The implication, therefore, is that observational practice led to sensorimotor learning via a common coding system (Brass & Heyes, 2005; Jeannerod, 1994; Prinz, 1997) that contains neural structures linking observation and execution (Buccino et al., 2004; Higuchi et al., 2012; Vogt et al., 2007). In this context, it is plausible that during observational practice the superior temporal sulcus (STS) provided visual input (based on the observed biological motion; see Allison et al., 2000) to the frontal mirror-neuron system where the goal of the observed action is coded, and the parietal mirror-neuron system where the motor specification of how the goal is achieved (Blakemore & Frith, 2005; Kilner, Hamilton, & Blakemore, 2007; Kilner, Paulignan, & Blakemore, 2003; Press, Cook, Blakemore, & Kilner, 2011). Accordingly, in the absence of sensorimotor (re)afference during observational practice, these coding operations must be operational in autism, and learning would have been based on repeatedly perceiving and comparing the observed *atypical* biological motion on *trial n*, to the same motion information on *trial n + 1*. Consequently, participants from both groups must have been effectively processing the biological motion characteristics of the atypical model.

The aforementioned sensorimotor processing is suggested to be tuned to biological motion kinematics (Candidi, Urgesi, Ionta, & Aglioti, 2008; Press, 2011) and thus biological motion stimuli are reported to facilitate imitation (Kilner et al., 2007; Longo, Kosobud, & Bertenthal, 2008). Indeed, Kilner and colleagues (2007) found the extent of motor interference from observing a stimulus significantly increased when it moved with biological kinematic profiles compared to constant velocity. Similarly, Longo et al. (2008) found automatic imitation effects were also increased

when stimuli moved in a biologically possible manner. With regards to autism, the ability to perceive and process biological motion has been shown to be functional (Cook, Blakemore, & Press, 2013; Cusack, Williams, & Neri, 2015; Hayes et al., 2018; Saygin, Cook, & Blakemore, 2010; Wild et al., 2012), and interestingly, Gowen and colleagues (2008) have shown that biological motion stimuli do facilitate imitation in autism. Like Kilner et al. (2007), this study investigated motor contagion in autism using both biological and non-biological stimuli. They found that in both the control and autism groups the observation of biological stimuli produced a significantly larger interference effect than a similar stimulus that moved with a constant velocity. Therefore, the previous findings (DeMyer et al., 1972; Hayes et al., 2016; R. P. Hobson & Lee, 1999; Rogers et al., 1996; Stewart et al., 2013; Wild et al., 2012) of poor performance during voluntary imitation in autism are unlikely to be associated with the processing and encoding of biological kinematics during observation. A plausible alternative could be related to general non-specific mechanisms (Sowden et al., 2016), such as those mediating theory of mind, executive function, sensorimotor learning, and overt visual attention.

Overt Visual Attention via Eye Movements

It has been suggested that differences in overt visual attention may contribute to voluntary imitation differences in autism (Gonsiorowski, Williamson, & Robins, 2016; J. A. Hobson & Hobson, 2007; Vivanti & Dissanayake, 2014; Vivanti, Nadig, Ozonoff, & Rogers, 2008). As a result, the atypical model used in chapters two, four and five consisted of a point light dot rather than a human actor in order to control for any potential modulation of overt visual attention related to social processing (Wang & Hamilton, 2012). In many imitation scenarios, an imitator is required to focus on multiple information sources during the action-observation phase of the

imitation process. Typically, the main factor that modulates imitation in autism is the presence of a social model (Wang & Hamilton, 2012). Here, an imitator often observes the facial region of the model, plus other areas that describe the motor characteristics of the to-be-imitated-action (e.g., limb configuration). In typically developing control populations, imitation has been shown to be modulated by eye contact (Wang, Newport, & Hamilton, 2010; Wang, Ramsey, & Hamilton, 2011). For example, Wang and colleagues (2010) asked participants to imitate intransitive hand movements as quickly as possible having observed a video of an actor either turn their head towards (i.e., direct gaze), or away (i.e., averted gaze) from the participant. They found that reaction times were significantly shorter in the direct gaze condition, showing that this condition facilitated imitation. This phenomena has been suggested to be related to social processes (Wang & Hamilton, 2014), whereby maintaining eye contact facilitates imitation by enabling an individual to maintain and promote social relationships (Chartrand & Lakin, 2013; Lakin & Chartrand, 2003). Therefore, given the known social differences in autism, it is not necessarily surprising that autistic participants focus their attention on non-socially oriented areas (e.g., the hand) rather than the eye region within the face during imitation (Vivanti & Dissanayake, 2014; Vivanti et al., 2008). For example, it has been suggested that autistic individuals have a reduced social interest, where attending to the face and/or eyes of model is not associated with social reward (Dawson, Webb, & McPartland, 2005; Grelotti, Gauthier, & Schultz, 2002), which could result in differences in overt visual attention. Furthermore, social factors associated with the model have also been proposed to modulate the action-observation network that is engaged to process biological motion (Wang & Hamilton, 2012). For example, and as outlined in the social top-down response model (STORM; Wang & Hamilton, 2012), the medial pre-frontal cortex (mPFC) and the temporo-parietal junction (TPJ)

play a key role (Hamilton, 2013, 2015) regulating the processing of biological motion in the superior temporal sulcus. Consequently, if a social stimulus had been used in the experimental chapters of this thesis this could have had a negative impact on how accurately the autistic participants could reproduce the atypical kinematic profile.

In addition to carefully controlling the social nature of the atypical and typical models, the use of a point light dot was intended to encourage the imitation of the atypical kinematics by removing the presence of end-state-targets. Therefore, rather than the model displaying a trajectory that was goal-directed to an end location target, the model ended in space. In this context, the environment has a limited amount of surrounding external information that could modulate the orientation of overt visual attention during action-observation. This manipulation is important as it has previously been shown that differences in visual attention during imitation in autism are not necessarily fully explained by social factors associated with the characteristics of the model (Vivanti et al., 2008; Wild et al., 2012). For example, Vivanti et al. (2008) highlight that the type of action being imitated (i.e., goal-directed) had a modulatory effect on autistic participants attention, suggesting that how observed actions are encoded and understood may differ between these conditions. Indeed, during the imitation of hand actions, it has been shown that autistic participants spent significantly more time focussing attention on the end-point of the observed action compared to controls who attended to the trajectory of the hand (Wild et al., 2012). As a result the autism participants spent more time performing saccades and fixations, compared to controls who spent more time in smooth pursuit (Takarae, Minshew, Luna, Krisky, & Sweeney, 2004; Wild et al., 2012). A consequence of this difference in the location of overt attention is that autistic participants are then less able to extract important kinematic information

(e.g., velocity) from the model, which modulates what information is imitated from the model. The goal-directed theory of imitation (GOADI; Bekkering, Wohlschlager, & Gattis, 2000) suggests that during imitation an individual engages top-down cognitive processes to develop a hierarchy of goals related to an observed movement. For example, the goal hierarchy could include the end-point (i.e., the light switch) and/or the goal of an action (e.g., to press the light switch), and the means of achieving the goals (i.e., limb velocity). The structure of the hierarchy is ranked in accordance to how a participant interacted with the model and environment. As a result, the lack of an apparent end-state-target in the stimuli from chapters two, four and five should therefore have resulted in the prioritisation of the trajectory within any cognitive hierarchy and therefore been the focus of attention during action-observation and imitation (Hayes, Hodges, Scott, Horn, & Williams, 2007; Horn, Williams, Scott, & Hodges, 2005).

Throughout this thesis the analysis of eye movements was focussed smooth pursuit eye movements and participants *tPSEV* during the action-observation phase of each trial. Smooth pursuit eye movements are used to maintain the retinal image of a moving stimulus on the fovea, which allows an individual to extract the velocity characteristics of the stimulus (McKee, 1981). This type of eye movement is controlled using an efference copy, as a predictor of how the eye needs to move in relation to the stimulus, and visual feedback related to the velocity and acceleration characteristics of the stimulus (Krauzlis & Lisberger, 1994). What is therefore of interest in the current thesis is that, in chapter four, although imitation accuracy was generally lower in the autism group than the control group, there were no general differences in the timing of the autism and control groups reaching peak smooth eye velocity when observing the moving stimulus. The discrete measure used showed participants from both groups modulated their *tPSEV* during smooth pursuit for the

atypical (Autism: 31.67 ± 6.33; Control: 30.37 ± 4.03) and typical models (Autism: 50.55 ± 7.55; Control: 52.25 ± 5.03). Furthermore, the increase in imitation accuracy across acquisition for the atypical model in the autism group did not correspond with any similar changes in *tPSEV*. Whereas there was a 9% improvement in imitation for the autism during this phase, inspection of the eye behaviour indicated no change across the same period. This finding demonstrates that both groups attended to this key kinematic landmark (i.e., peak velocity) during action-observation similarly. The analysis of eye movements from chapter five also found no differences in how the participants of each group reached peak smooth eye velocity, in relation to an observed model, during either observational practice or imitation learning. As a result, the findings from chapters four and five highlight that both groups had the opportunity to extract the observed velocity characteristics (McKee, 1981) as the stimuli reached peak velocity. Moreover, although not directly examined within this thesis they also suggest that it is likely that both groups also showed similar overt visual attention throughout the entire duration of both the atypical and typical models. That is not to say that visual attention in autism is not differentially affected by factors such as the presence of goals (Wild et al., 2012) and/or social stimuli (Vivanti & Dissanayake, 2014; Vivanti et al., 2008) as described above, but rather, that these differences can be controlled by suitably designed protocols.

The eye movement findings were further emphasised by participants responses in the debrief questionnaire used in chapter five. When asked "*What did you do during the observation phase?*" participant 12 from the autism group said, "*I first acknowledged the structure of when it [the model] was fast and when it was slow, as I wanted to get the pattern right. Then secondly, I tried to anticipate the speed and see if there was any difference between the thirty times that I saw it*". However, it is worth noting that in the observational practice experiment participants

were given specific instructions to “observe the horizontal movement made by the model with the intention to overtly reproduce the movement trajectory following action-observation”. The use of an instruction to direct attention towards specific aspects of a model have previously been shown to facilitate the imitation of atypical biological kinematics following observational practice (Hayes et al., 2014). For example, they used a selective-attention (Bach et al., 2007; Longo & Bertenthal, 2009) protocol where one group received specific instructions that stated, “while observing the model the learn the time goals, you should focus your attention onto the characteristics of the model’s movement trajectory with the intention to imitate the exact trajectory”, whereas the other experimental group were provided general instructions to “observe the model with a view to learning the movement time goals” (Hayes et al., 2014). They found that the group which received specific instructions reproduced the observed atypical kinematic profile more accurately, suggesting that the instructions enabled more accurate coding of biological motion (Hayes et al., 2014). This top-down modulation of imitation accuracy has since been examined during voluntary imitation in autism (Hayes et al., under review). However, in this study selective attention instructions were not shown to facilitate imitation in autistic participants. Importantly, these instructions which were designed to direct attention toward the model’s trajectory also had no impact upon the eye movements of the participants. This finding therefore suggests that the instructions used in chapter five of this thesis are unlikely to have modulated eye behaviour in the autism group. Consequently, the current findings suggest that imitation of atypical biological kinematics in autism are unlikely to be directly underpinned by differences in overt visual attention as the data shows both groups were attending similarly at the key kinematic landmark of peak velocity.

6.3 Implications for sensorimotor integration in autism spectrum disorders

Motor learning

A contributing factor to the imitation differences presented in the thesis may therefore be altered sensorimotor integration, which is the capacity of the CNS to process and integrate sensory information from multiple sources (i.e., vision, proprioception) whilst simultaneously transforming this information into a motor output (Machado et al., 2010). The integration process underpins the ability to learn new motor skills (i.e., motor learning) via the development of internal action models that represent the associations between the to be generated motor command, the sensory (e.g., vision and proprioception) consequences of the movement on the limb, and any environmental constraints (Krakauer & Shadmehr, 2007). The neurophysiological basis of sub-cortical and cortical sensorimotor integration (Monfils, Plautz, & Kleim, 2005) is suggested to occur within the basal ganglia and cerebellum (Doyon et al., 2009; Shadmehr & Krakauer, 2008), as well as the association areas (i.e., pre-frontal cortex, parietal cortex) and pre-motor and motor cortex (Eliassen, Souza, & Sanes, 2001). The specific contributions of these keys regions are proposed to be that the basal ganglia aids in the control of a movement and the associated costs in effort and reward, whilst the cerebellum contributes to predicting the sensory consequences that are represented within an internal action model (Shadmehr & Krakauer, 2008). In autism, a structural difference in the basal ganglia is suggested to be associated with differences in motor ability (Qiu, Adler, Crocetti, Miller, & Mostofsky, 2010), and atypical neural activation in associated cortical areas have been demonstrated during motor sequence learning (Müller, Cauich, Rubio, Mizuno, & Courchesne, 2004; Müller, Kleinhans, Kemmotsu, Pierce, & Courchesne, 2003). For example, during the learning of a finger tapping sequence, Müller et al. (2004) found greater activation of the premotor cortex occurred during

the latter stages of learning in autistic participants compared to lower activation patterns in control participants. The reduction in premotor cortical activity for the control group (Jenkins, Brooks, Nixon, Frackowiak, & Passingham, 1994) indicates that as motor adaptation progressed over practice the overt motor response became less stimulus driven (De Jong, Frackowiak, Willemsen, & Paans, 1999; Müller, Kleinhans, Pierce, Kemmotsu, & Courchesne, 2002). Whereas, the greater activation patterns in autistic participants suggests more stimulus driven sensorimotor control that is underpinned by ineffective action model formation (Müller et al., 2004).

Despite these findings, behavioural evidence for the effective formation of internal action models in autism has been provided from motor adaptation (Gidley Larson et al., 2008) and motor learning (Hayes et al., 2018) protocols. Gidley-Larson and colleagues (2008) showed that having performed a ball throwing task with a visual perturbation (i.e., prism goggles), both autistic and control participants showed an immediate decline (i.e., after-effects) in motor performance when the goggles were removed . The implication being that both groups had formed an internal action model that represented the expected sensory and motor consequences associated with the perturbed condition and as result this internal action model was no longer effective once the perturbation was removed. Both groups did however demonstrate a return to the accuracy they had shown during the previous condition after they had attained more experience of the task without any perturbation. Thus, showing they had updated their internal action model to represent the expected sensory and motor consequences associated with this new condition. Similarly, Hayes et al. (2018), using the same VSTT as chapter three of the current thesis, found that although the autism group were generally less accurate and more variable than controls, both groups showed greater timing accuracy following an acquisition period. The findings of the retention test also showed that this adaptation effect

persisted when knowledge of results was removed, therefore indicating that both groups had developed new internal action models.

Like the aforementioned studies (Gidley Larson et al., 2008; Hayes et al., 2018), the findings from chapter three of this thesis provide further behavioural evidence of the successful formation of internal action models in autism. Here, participants completed thirty acquisition trials where they performed a VSTT with a criterion movement time of 1700 ms. Knowledge of results regarding trial performance in relation to the criterion was provided following each trial. As a result of this acquisition period, the autism group successfully reduced their *temporal constant error* by an average of 786 ms, and their *temporal variable error* by 269 ms. These adaptation effects indicate that that motor learning processes, which enable the development and continued refinement of internal action models, are functional in autism. Similarly, the control group showed a significant reductions in *both temporal constant error* (529 ms) and *temporal variable error* (347 ms) across the acquisition period. Furthermore, analysis of participants relative timing structures during the VSTT revealed that both groups made comparable significant directional (e.g., increase in segment 1; and decreases in segment 2 and 3) adaptations to the proportion of time spent executing each segment. These changes led to both groups executing comparable movements, and indicated that the sensorimotor processes underlying the emergence of self-selected (preferred) (Heuer & Schmidt, 1988) relative timing structures in autism is operational and comparable to a matched-control group. Further highlighting that motor learning processes occurred similarly in the autism and control groups (Gidley Larson et al., 2008; Hayes et al., 2018).

With regards to the previously discussed specific differences during imitation (DeMyer et al., 1972; Hayes et al., 2016; R. P. Hobson & Lee, 1999; Rogers et al., 1996; Stewart et al., 2013; Wild et al., 2012) in autism, the findings of chapter three

alone, where action model formation was shown to be functional (Gidley Larson et al., 2008; Hayes et al., 2018), do not exclude the possibility that problems in cortical sensorimotor integration and motor learning are a contributing factor. The findings from chapter four show that although both groups did successfully modulate their behaviour in relation to whether the atypical (Autism: 28.46 ± 8.96; Control: 20.99 ± 7.67) or typical (Autism: 36.76 ± 9.88; Control: 34.52 ± 9.29) model was being imitated, the autism group were less accurate overall than their control counterparts. Indeed, the autism group's pre-test performance (32.25 ± 8.36) for imitating the atypical model, when presented in a randomised order alongside the typical model, was comparable to the findings of Hayes et al. (2016). The action-observation phase of imitation relies on successfully utilising visual information. As discussed previously, the lower-level processing of biological kinematics is likely to be functional in autism despite there being differences in how visual information is used during action model formation (Haswell, Izawa, Dowell, Mostofsky, & Shadmehr, 2009; Izawa et al., 2012; Marko et al., 2015). For example, it has been shown that having learned to control a novel tool, autistic participants were less able to generalise the developed internal action model to a condition that was visually similar than they were to one which was physically similar (Haswell et al., 2009). This has resulted in the suggestion that autistic individuals have an over reliance on proprioception during the formation of internal action models, which may result in the discounting of visual information (Haswell et al., 2009; Izawa et al., 2012; Marko et al., 2015). This may provide a potential explanation of the imitation differences in chapter four, where only the control participants could accurately imitate the *atypical* model during the pre-test. It is possible that the limited visual information provided when observing the *atypical* model during chapter four's pre-test was inadequate for autistic participants to form an accurate internal action

model, and may have been discounted, but was sufficient for the control group to accurately replicate the atypical model.

How autistic participants utilise sensory information during internal action model formation was examined in chapter five. Here, an observational practice protocol was used to examine the development of internal action models independent of any active contributions of the peripheral motor system (Berger et al., 1970; Berger & Hadley, 1975). As previously discussed in relation to the processing and encoding of biological kinematics during observation, both groups successfully adapted the pre-test performance (Autism: 40.81 ± 9.19; Control: 42.97 ± 8.32) that resembled the velocity profile of the typical model, to one which resembled the observed atypical model (Autism: 30.80 ± 7.49; Control: 29.78 ± 13.47). In addition, both groups showed significant reductions in temporal constant error (Autism: %Δ = 80; Control: %Δ = 61) as a function of the thirty observational practice trials. Therefore, these findings suggest for the first time that autistic participants formed a novel internal action model (Gidley Larson et al., 2008; Hayes et al., 2018) across observational practice that accurately represented the temporal and velocity characteristics of an observed model. Moreover, this shows that the absence of proprioceptive information does not prohibit motor learning in autism, despite the suggestion that this information source may be prioritised by this population (Haswell et al., 2009; Izawa et al., 2012; Marko et al., 2015).

It should be noted however that it is possible that the representation of actions during imitation and observational practice may be independent of sensory modality {Meltzoff, 1997 #686}. The active intermodal mapping (AIM) theory of proposes that imitation is a function of a specialised system where information from observed stimuli are coded within an amodal representation, rather than a more general mechanism involving the lower-level encoding of biological motion as

previously discussed. AIM therefore suggests that observational learning is matching-to-target process whereby an individual compares their end-state with the observed state and corrects their movement via the aforementioned amodal code {Meltzoff, 1997 #686}, rather than perception resulting in direct activation of the sensorimotor system {Heyes, 2001 #401}. This explanation however is unlikely to fully account for the findings in chapter five. For example a previous study investigating sensorimotor training {Catmur, 2007 #461} examined whether the sensorimotor system is reconfigured following the observation of incompatible movements. Here a 'compatible' group performed index finger movements, whilst simultaneously observing similar index finger movements, whereas an 'incompatible' group performed the same index finger movement, but whilst observing little finger movements. Following this training phase they measured TMS-induced motor evoked potentials (MEP) in the little finger of participants whilst observing finger movements. They found that in the incompatible group their sensorimotor systems had indeed been reconfigured as MEPs were greater when observing index finger movements compared to little finger movements. Highlighting the use of a general mechanism {Heyes, 2001 #401}, over a specific mechanism for translating visual information to a motor output {Meltzoff, 1997 #686}.

Regardless, the introduction of proprioceptive feedback during the imitation learning protocol in chapter five did also highlight potential differences in how the visual and proprioceptive sensory modalities are processed via a learned action model in autism. As displayed in *Figure 5.3.A*, and compared to the autism group (30.34 ± 9.08) in the early phase of imitation, the control group imitated a velocity profile closer to that of the atypical model (25.34 ± 8.10 %) which did not significantly improve across the imitation trials. Whereas the autism group

demonstrated significant adaptation across the imitation trials such that peak velocity occurred earlier in the movement, and closer to the atypical model at the late phase (27.53 ± 8.56). The findings of chapter five suggest that whilst biological motion information is processed via a common coding system (Brass & Heyes, 2005; Jeannerod, 1994; Prinz, 1997) during observational practice leading to action model formation in autism, differences are apparent when the action model is engaged for integrating sensorimotor information during the movement reproduction phase of imitation. The aforementioned differences indicate that the autism group were less effective at integrating reafferent information (i.e., vision and/or proprioception) when updating a learned internal action model (Elliott et al., 2001; Wolpert et al., 2011) in order to accurately imitate atypical biological kinematics.

Previous studies (Cook, Swapp, Pan, Bianchi-Berthouze, & Blakemore, 2014; Haswell et al., 2009; Hayes et al., 2016; Izawa et al., 2012; Mostofsky & Ewen, 2011) have also indicated differences in the effectiveness of sensorimotor integration. For example Cook and colleagues (2014), who investigated motor contagion in autism, argue that one potential reason for the lack of an interference effect in the autism group is that whilst control participants may classify similar observed movements under one common template, those with autism rely on the incoming sensory information from each observed movement to produce a specific representation of it. Therefore, within the autistic sensorimotor system, observed movements may not produce an interference effect as they do not resonate with a pre-existing movement within their motor repertoire (Cook et al., 2014). This therefore raises the suggestion that the findings of chapter five, where the benefit of reafferent signals during the imitation learning protocol was immediate for the control group but not for those with autism, may relate to the specificity of learning hypothesis (Proteau, 1992; Proteau, Marteniuk, Girouard, & Dugas, 1987; Proteau,

Marteniuk, & Lévesque, 1992). This hypothesis suggests that any action model developed during learning is specific to the sensory conditions in which it was developed. Therefore, in relation to the observational practice phase of chapter five, the internal action model acquired would be specific to the visual sensory consequences of the observed action as participants did not gain any physical experience of the modelled action until attempting to perform it from memory during the post-test. The specificity of internal action models formed via observational practice has previously been examined by Hayes, Elliott, and Bennett (2010). They asked participants to learn a motor sequence with a criterion movement time of 1200 ms via either physical practice or observational practice. Following the learning period, where there was a 1:2 gain relationship between the mouse and cursor participants were transferred to either a congruent condition, with the same gain relationship, or an incongruent condition, where a new gain relationship of 1:1 was used. It was expected that if general action models were produced following either physical practice or observational practice then both groups should be able to successfully transfer to the incongruent condition. If, however, action model formation during observational practice is specific to the observed visuo-motor relationship then this group should be at a significant disadvantage when transferred to the incongruent condition. This was however not the case, with no significant differences between the two groups in how accurately they reproduced the motor timing goal in either condition, suggesting that general internal action models are formed as function of observational practice despite there being no contribution of reafference (Hayes et al., 2010). It is therefore likely that findings of chapter five are evidence of altered sensorimotor integration in autism, resulting in the less effective processing and consolidation of reafference during the imitation learning protocol.

Problems during sensorimotor integration may be further exacerbated by the use of randomised trial orders and may contribute to why previous studies (Hayes et al., 2016), have shown autistic participants to be significantly less accurate than matched-controls at imitating atypical biological kinematics. During a randomised trial order sensorimotor information from trial *n* (e.g., atypical model) is likely to differ to trial *n+1* (e.g., typical model), which can therefore impact the continued development of any internal action models via the comparison of expected (efference) and actual (reafference) sensorimotor consequences (Elliott et al., 2001; Wolpert et al., 2011). In contrast fixed trial orders, where trial *n* is the same as trial *n+1*, can facilitate these comparisons (Kantak & Winstein, 2012) enabling an internal action model to be continually refined so that the movement can become more similar to that of the observed model. An example of a fixed trial order has already been discussed in relation to the imitation learning findings from chapter five, however this was in relation to the development of an already existing internal action model. Chapter four, in contrast, does provide evidence of how fixed trial orders affect the formation of internal action models for novel movements. Here, following a randomised pre-test, participants completed an acquisition phase where they imitated both the atypical and typical models for thirty times, in a fixed trial order. As a function of this acquisition phase the autism group became more accurate (%Δ = 9) in replicating the atypical kinematics of the model, suggesting that the use of a fixed trial does facilitate (Elliott et al., 2001; Wolpert et al., 2011) internal action model formation in autism (Gidley Larson et al., 2008; Hayes et al., 2018). Importantly this motor learning effect was also demonstrated when comparing the autism group's pre-test (32.25 ± 8.36) and post-test (28.10 ± 9.68) performances, where on average the peak occurred 4.15 units earlier. Both the pre-test and post-test used a randomised trial order meaning it is likely that this change was a function of

an internal action model that was developed during the acquisition phase. Overall, these findings, in combination with those of chapters three and five provide evidence of functional motor learning processes in autism across three contexts: sequence learning, imitation and observational practice. Participants from the autism groups were able to successfully form internal action models (Gidley Larson et al., 2008; Hayes et al., 2018), although general differences in timing error (Chapter three; Hayes et al., 2018), and imitation accuracy (Chapter four; Hayes et al., 2016) persisted.

Feedforward contributions to motor execution

The above motor differences could be a function sensorimotor integration during feedforward processes, such as state estimation, motor planning and efferent control. As previously stated, sensorimotor integration is the capacity of the CNS to process and integrate sensory information from multiple sources (i.e., vision, proprioception), whilst simultaneously transforming this information into a motor output (Machado et al., 2010). In order to accurately execute an action, humans must utilise this sensory information alongside pre-existing models from their motor repertoire. This enables them to form an accurate state estimate that can be used to create predictions (Molinari, Restuccia, & Leggio, 2009). These predictions can then facilitate both the generation of a motor command via planning and online motor control (Elliott et al., 2010; Ghez, Hening, & Gordon, 1991; Miall & Wolpert, 1996; Wolpert & Flanagan, 2001; Wolpert & Kawato, 1998) and form the basis of an inverse model (Wolpert, Ghahramani, & Jordan, 1995; Wolpert & Kawato, 1998).

Differences in motor planning have often been reported in autism (Fabbri-Destro, Cattaneo, Boria, & Rizzolatti, 2009; Glazebrook et al., 2006; Glazebrook, Elliott, & Szatmari, 2008; Glazebrook, Gonzalez, Hansen, & Elliott, 2009; Nazarali,

Glazebrook, & Elliott, 2009; Rinehart et al., 2001). One example is that autistic participants take longer to react to changes within their environment when performing motor actions than control participants (Nazarali et al., 2009). Participants were required to plan and execute a manual aiming movement to a target with one their hands, but the location of the target or the hand to be used was changed on 20% of trials. This resulted in a greater increase in reaction times for the autistic participants, highlighting potential differences in autistic participants ability to integrate sensory information and translate this into a motor output (Machado et al., 2010). A key aspect of this process is being able to identify sensorimotor patterns from the environment that fit with pre-existing models from the individual's motor repertoire (Molinari et al., 2009). Consequently, the use of a randomised trial order in previous imitation studies (Hayes et al., 2016) may have not only impacted the formation and development of an internal action model (Elliott et al., 2001; Wolpert et al., 2011) but also had a negative effect on motor planning. This is because during this randomised trial order there was a trial-to-trial need to plan and specify the force requirements of two separate velocity profiles (i.e., atypical & typical), one of which (atypical) did not already exist within the sensorimotor repertoire of the participants. Indeed, the autistic participants from chapter four were significantly more accurate (%Δ = 17) in their imitation of the atypical model during the middle-acquisition phase (26.68 ± 9.03), where a fixed trial order was used, compared to the random pre-test (32.25 ± 8.36). This change was not present in the control group (pre-test: 21.35 ± 9.24; middle-acquisition: 20.20 ± 7.67). These findings therefore suggest that, as well as facilitating action model formation, the fixed-trial order also provided processing benefits (Kantak & Winstein, 2012) which allowed information from trial n to be to integrated more effectively, facilitating motor planning for trial $n + 1$ (Elliott et al., 2001; Wolpert et al., 2011) as the repeated constructing and

reconstructing (Cross, Schmitt, & Grafton, 2007; Kantak, Sullivan, Fisher, Knowlton, & Winstein, 2010) of different motor plans (i.e., Atypical and Typical) could produce an interference effect (Shea & Morgan, 1979). That is not to say that the facilitation of motor planning was necessarily the primary contributing factor to the observed improvements in how autistic participants imitated the atypical model in chapter four. Another of the planned comparisons examined imitation accuracy from late acquisition compared to the post-test. Here, if planning issues related to a randomised trial-order were solely responsible for differences in imitation accuracy in autism, autistic participants were expected to be less accurate in the post-test as they returned to this trial-order. This was not the case, with the autism group showing no significant change from late acquisition (26.17 ± 8.32) to the post-test (28.10 ± 9.68). Imitation differences in autism are therefore suggested to be related to broader sensorimotor integration issues which encompass both feedforward processes and action model formation, which were facilitated by the fixed trial order used during acquisition (Elliott et al., 2001; Wolpert et al., 2011), rather than specifically motor planning.

The availability of advance information, such as the predictable trial order used in chapter four, however is not necessarily utilised effectively by autistic participants (Rinehart et al., 2001). For example, Rinehart and colleagues (2001) interrupted participants performance of a reciprocating movements between two targets by introducing ‘oddballs’ where an additional target would be illuminated signalling participants were required to move to target that was not ordinarily part of the sequence. As participants had been informed this would only take place once per trial, the planning of the movement immediately following this should have been facilitated by this advance knowledge. Although this was the case, for the control group, autistic participants showed no benefit of this advance knowledge with motor

preparation times being similar to, or in some cases slower than, those prior to the 'oddball'. Consequently, execution differences in autism related to feedforward issues are not to be specifically related to predictable trial orders. Indeed, in chapter three despite the autism (%Δ = 64) and control groups (%Δ = 65) showing improvements in *temporal constant error* as a function of the acquisition phase, the autism group (594.05 ± 437.57 ms) continued to produce less accurate movements than the control group (290.35 ± 206.48 ms). In addition, the autism group's (380.20 ± 107.35) movements were also more variable than the control group (289.91 ± 79.98 ms) once feedback was removed. Similarly, in chapter five, the autism group (pre-test: 293.58 ± 139.63 ms; post-test: 270.50 ± 162.38 ms) were also shown to have greater variability in their motor outputs during the observational practice protocol than their control counterparts (pre-test: 211.34 ± 103.74 ms; post-test: 215.56 ± 86.97 ms), despite comparable performance in replicating the atypical velocity profile of the observed model in the post-test (Autism: 30.80 ± 7.49; Control: 29.78 ± 13.47).

Elongated and more variable movements, like those shown in chapters three and five, have also been reported elsewhere (Glazebrook et al., 2006; Hayes et al., 2018). Similar to chapter three, Hayes and colleagues (2018) showed greater total error in the autism group when performing a three-segment motor sequence despite evidence for the functional formation of internal action models. Moreover, in a manual aiming study conducted by (Glazebrook et al., 2006) it was reported that autistic participants movement times were on average 91 ms longer in duration than controls. What is highlighted however, is that proportionally the movements of autistic and control participants were similar (Elliott et al., 2010). That is, although the magnitudes of kinematic markers, like peak velocity, were lower in the autism group they occurred at a similar time related to the overall movement time. If this

were to be applied to the typical model used throughout this thesis, for example, the velocity profile of this movement executed by an autistic individual would still have a bell-shaped profile, but it would appear longer and flatter (Elliott et al., 2010; Glazebrook et al., 2006). As a result these differences have suggested to be indicative of problems specifying the required muscular forces in autism (Elliott et al., 2010), resulting in the lower than optimum forces being produced. Suggesting that problems in forming a state estimate and motor planning could impact autistic individuals abilities to integrate sensory information, such as the distance between the limb and the target, and transform this information into an effective motor output (Machado et al., 2010).

Consequently, efferent control could also be affected in autism. When a motor command is generated, as well as being sent to the muscles, it is also used as a reference of the to-be-executed action (Evarts, 1973). This efferences copy can be then compared against the actual movement, allowing early movement adaptation via graded adjustments to the muscular forces being produced to drive the limb, before afferent information can be processed (Elliott et al., 2010; Miall & Wolpert, 1996; Wolpert & Flanagan, 2001). In manual-aiming movements it has been proposed that this takes place between movement initiation, and peak acceleration (see *Figure 1.2*; Elliott et al., 2010), and it is for this reason spatial variability was examined at this kinematic landmark in chapter three. Greater spatial variability in the autism group here would suggest a larger discrepancy between the actual efference of the executed action and the prediction made via the efference copy, and as a result highlight any potential issues in the specification of muscular forces (Elliott et al., 2010). Indeed, the autism group did show overall significantly greater *sdPA* during both acquisition (10.27 ± 2.51 mm) and retention (9.32 ± 3.70 mm) than their control counterparts (Acquisition: 8.78 ± 2.36 mm; Retention: 7.20 ± 2.36

mm). It is however important to note that a significant main effect for phase was present in *sdPA* during acquisition. Highlighting as discussed in the preceding section that sensory feedback over consecutive trials was facilitating the continuous refinement of the internal action model (Meyer, Abrams, Kornblum, Wright, & Keith Smith, 1988) in autism. Nevertheless, whilst this process did facilitate reductions in spatial variability during motor execution for both groups, the specific difference in *sdPA* persisted. This implies that although the efficacy of an internal action model may facilitate feedforward processes, like motor planning, in both autism and control groups, the observed differences may be independent of this and potentially the product of an autism specific sensorimotor system (Cook, 2016; Mostofsky & Ewen, 2011).

The argument that differences motor execution, related to feedforward contributions, may be the product of an autism specific sensorimotor system (Cook, 2016; Mostofsky & Ewen, 2011) is supported by a proposal made by Latash and Anson (1996). They suggest that altered motor execution in special populations such as Parkinson's disease and Down's syndrome could related to strategies developed to compensate for differences in processing related to the CNS, rather than inherently different. In chapter three, the significant difference between the autism and control groups in spatial variability that was present at peak acceleration had dissipated upon reaching peak velocity in both acquisition (Autism: 14.08 ± 4.81 mm; Control: 12.49 ± 4.28 mm), and retention (Autism: 11.95 ± 5.33 mm; Control: 12.31 ± 6.01 mm). Importantly a similar finding was also shown by Glazebrook et al. (2006), who also found that differences in spatial variability at peak acceleration were no longer present upon reaching peak velocity. At this later stage of a movement afferent feedback, like vision, has had enough time to processed and compared to the expected sensory consequences of a movement (see *Figure 1.2*; Elliott et al., 2010).

This allows for online motor control to take place. It could therefore be the case that differences in movement times for autistic participants (Glazebrook et al., 2006; Hayes et al., 2018) may also be explained by a potential strategy in which slower movements are produced by autistic individuals so that sensory feedback can be used to overcome issues in feedforward control (Elliott et al., 2010). For example, in chapter three, the autism group spent proportionally more time in the final segment than the control group. This elongated segment movement time might be an example of such a strategy which the autistic participants in order to accommodate a noisier autistic sensorimotor system (Glazebrook et al., 2006) and/or any potential issues in feedforward processing (Nazarali et al., 2009; Rinehart et al., 2006) . Therefore, by spending more time in the final segment they could better utilise the available visual feedback to home in on the final target to terminate the movement accurately (Elliott et al., 2010; Saunders & Knill, 2005) and then to use the information extracted during visual processing for offline motor planning for the next trial (Khan, Elliott, Coull, Chua, & Lyons, 2002). Mosconi et al. (2015) also draw a similar conclusion having found that during low force contractions the initial force produced by autistic participants was less accurate than for controls, resulting in a greater peak rate of force production and overshooting. Whereas in larger force contractions, which are typically associated with greater movement durations, these differences were not present. Further highlighting that autistic participants may adopt movement strategies which facilitate the processing of visual sensory feedback to compensate for feedforward issues, such as the specification of muscular forces (Elliott et al., 2010; Glazebrook et al., 2006), which they experience during motor execution.

6.4 Wider Considerations & Limitations

Diagnosis

Differences in sensorimotor processes (Kaur, Srinivasan, & Bhat, 2018; Marko et al., 2015; Mostofsky & Ewen, 2011) may underpin the delays seen in developmental milestones - e.g., lying, righting, sitting and crawling (Teitelbaum, Teitelbaum, Nye, Fryman, & Maurer, 1998), and potentially contribute to bilateral difficulties in social cognition (Cook, 2016). Indeed, indicators of motor impairment have been shown to correlate with autism severity, as well as a bias towards the perception of non-biological motion (Cook et al., 2013). Relationships were also demonstrated during an investigation of action model formation (Haswell et al., 2009), where a greater reliance on proprioceptive feedback was indicative of greater social and imitative impairments. It has therefore been proposed that motor differences in autism impact an individual's ability to recognise and understand the actions of others (Cook, 2016). As demonstrated across chapters three, four and five of the current thesis, individuals with autism are able to form new internal action models and adapt their motor output similar to control participants (Gidley Larson et al., 2008; Hayes et al., 2018). As similar motor experience has been shown to facilitate action perception (Casile & Giese, 2006), it is suggested that during social interactions autistic individuals point of reference is their own motor system, which has been characterised to be noisier (Gowen & Hamilton, 2013), and may therefore be incongruent with that of who they are attempting to interact with (Cook, 2016).

For these reasons, discussions on how the motor system impacts autism are increasing in prominence (Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Gowen & Hamilton, 2013), with the use of kinematic events also having recently been proposed in the diagnosis of autism (Li, Sharma, Meng, Purushwalkam, & Gowen, 2017). The current thesis identified that increased *sdPA* could be a potential kinematic biomarker of the autism phenotype. It is however important to note that, in the case of chapter three, although these differences were evident throughout the

study a phase effect was also present whereby spatial variability reduced as a function of acquisition (*see Figure 3.4*). Future research should therefore examine whether following extended practice this difference persists, or whether both autism and control participants ultimately demonstrate similar variability. As shown in chapter five, although processes related to the formation of internal action models appear to be intact in autism (Gidley Larson et al., 2008; Hayes et al., 2018) the transfer from the post-test to the imitation learning protocol suggested that the control group were able to more efficiently integrate the additional sensorimotor information now available and adapt their motor output more quickly (*see Figure 5.3.A*). It may therefore be possible that, given enough trials, the differences shown in chapter three may diminish. If this is the case, increased spatial variability at peak acceleration would not be a viable kinematic marker for autism. However, if differences were to persist it would demonstrate that it may have a potential future use in the diagnosis of autism spectrum disorders (Li et al., 2017).

Social Modulation

The findings from chapters four and five extended understanding of lower-level sensorimotor processes in autism, demonstrating that autistic participants can represent atypical biological kinematics during action-observation. As autism is often characterised by difficulties in social interaction and communication (American Psychiatric Association, 2013), an important extension of these findings would be to examine this processing during tasks of a social nature. The social top-down response modulation (STORM) model (Wang & Hamilton, 2012) suggests the medial prefrontal cortex (mPFC) plays a role in evaluating social context and therefore controlling which actions are represented. For example, in control populations imitation has been shown to be modulated by eye contact (Wang et al.,

2010), with direct gaze resulting in increased mPFC activity (Wang et al., 2011). Additionally, cognitive primes have also been used to modulate imitation behaviour (Cook & Bird, 2011). Here prosocial sentences were shown to significantly increase the imitation effect of an automatic imitation protocol compared to non-social sentences. Activity in the mPFC is also suggested to show a direct link between the control of imitation and mentalising processes (Brass, Ruby, & Spengler, 2009), with the ability to inhibit an imitative response being shown to correlate significantly with an ability to attribute mental states (Spengler, von Cramon, & Brass, 2010).

In autism however, the use social primes have been shown not to facilitate imitation. For example, a prosocial prime did not modulate automatic imitation for autistic participants but did in the control group (Cook & Bird, 2012). Although this was considered when selecting to use the non-human agent of a white dot throughout this thesis in order to examine imitation without any modulatory effects of social context, it does limit how the current findings can be related to those examined within such a context (J. A. Hobson & Hobson, 2007; Vivanti & Dissanayake, 2014). The addition of a secondary stimulus, such as a human actor, to the current protocols used in this thesis would therefore facilitate the examination of how imitation autism is modulated by altered social top-down control. Here, if the encoding of atypical biological kinematics is modulated by social context (Spengler, Bird, et al., 2010), the *tPHV* produced by the autism group could be expected to be similar to that of the pre-test in chapter four (32.25 ± 8.36), where imitation accuracy was not facilitated by the fixed trial order (Elliott et al., 2001; Wolpert et al., 2011). Whereas, if the social context does not modulate imitation in autism, imitation accuracy would be expected to be more similar to that of the chapter four's post-test (28.10 ± 9.68).

Longitudinal Research

All the autistic volunteers, and their control counterparts, who participated in the research undertaken within this thesis were adults (see *Table 6.1*). This therefore raises the question of whether the findings of the current thesis would be replicated in younger samples. As much of the existing literature on action model formation (Gidley Larson et al., 2008; Haswell et al., 2009) and imitation (Hamilton et al., 2007; Rogers et al., 1996; Stewart et al., 2013) has been with children and adolescents, one way of answering this question would be to adapt the experimental protocols used here for studies with these populations.

Table 6.6.1: Summary of autistic and matched control participants' ages for each chapter.

	Autism		Control	
	Mean chronological age in years (SD)	Range	Mean chronological age in years (SD)	Range
Chapter Three (*n* = 26)	25 (7)	18-44	25 (7)	18-45
Chapter Four (*n* = 20)	27 (8)	18-48	25 (8)	18-46
Chapter Five (*n* = 20)	25 (7)	18-44	25 (7)	18-45

However, what may be of greater interest would be longitudinal data that examined the development of both motor and imitation abilities across life milestones in both autism and control groups. In the case of imitation it has previously been shown that imitation ability correlates significantly with the chronological age of autistic participants (Stewart et al., 2013). Suggesting that although the autistic participants were generally less accurate at imitation than their control counterparts, older autistic adolescents tended to be more accurate than the

younger participants. It would therefore be of interest to further understand any changes across development when considering the known links between imitation and social interaction, a core deficit of autism. Moreover, motor differences have also been highlighted as a potential contributing factor to social difficulties in autism (Cook, 2016). The development of the social skills is suggested to require the exploration of our environment (K. L. Marsh, Richardson, & Schmidt, 2009), and to engage in such a process a functional motor repertoire is needed. Delays in motor development in autism have been evidenced during infancy (for a review see Bhat, Landa, & Galloway, 2011), with key differences being related to praxis (Mostofsky et al., 2006), gait (Calhoun, Longworth, & Chester, 2011) and motor planning and control (Hughes, 1996) as discussed throughout this thesis. Longitudinal studies would therefore allow for the examination of motor development in conjunction with social development to better understand how these important life skills impact upon and facilitate each other across key developmental milestones.

Intervention

As described previously not only did the current thesis confirm the functionality of lower-level sensorimotor processes (chapter five) and the formation of internal action models (chapters three, four and five) in autism but it also demonstrated an effective protocol for facilitating the imitation of atypical biological kinematics (chapter four). Whereas previous research (Hayes et al., 2016) adopted a randomised trial-order, in the current thesis a fixed trial order was shown to facilitate the encoding of atypical biological kinematics (Elliott et al., 2001; Wolpert et al., 2011), resulting in more accurate imitation in autism (chapter four).

Furthermore, chapter five has demonstrated that adaptation can occur similarly between control and autistic groups, but those with autism may require more time

and exposure to a stimulus. These findings could therefore be used to inform interventions in autism.

Video based interventions have been shown to be effective for training social and communication skills in autism (for a review see Shukla-Mehta, Miller, & Callahan, 2010). They have also been shown to improve imitation skills (Cardon, 2013; Cardon & Wilcox, 2011). For example, following a twelve week intervention where participants imitated gestures shown on an iPad, participants showed increases in their gestural imitation skills (Cardon, 2013). Moreover, participants also showed additional benefits from the intervention showing development in their receptive and expressive language as function of the video modelling imitation training. Evidence therefore suggests that video based interventions can be an effective tool for skill development in autism, and importantly are perceived positively by caregivers (Cardon, Guimond, & Smith-Treadwell, 2015). The outlined findings from the current thesis could therefore be used to facilitate the development of new skills in autism. By presenting the to-be-learned skills in a repeated and predictable manner which will enable more effective sensorimotor integration (Elliott et al., 2001; Wolpert et al., 2011) the efficacy of such interventions could be potentially improved.

Developmental Coordination Disorder (DCD)

It should also be noted that the exclusion criteria of the experimental chapters in this thesis included the screening (via self-report) of any comorbid neurological or psychiatric conditions. As a result any potential participants with an additional diagnosis of DCD were excluded. DCD is associated with difficulties in motor coordination which can significantly impact the day-to-day lives of those diagnosed {American Psychiatric \Association, 2013 #427}. Although DCD and autism are

independent of one another it has been reported that they possess shared characteristics {Sumner, 2016 #727}. As discussed throughout this thesis motor differences are present in autism (for a review see Fournier et al., 2010), but it is also understood that social problems that synonymous with autism may also be experienced in DCD {Sumner, 2016 #727;Cummins, 2005 #729;Dewey, 2002 #728}. For example, {Dewey, 2002 #728@@author-year} found that children with DCD often also showed problems in attention, as well as forming and maintaining social relationships. The degree of this overlap in autism and DCD was examined by Sumner et al. (2016), who found that motor skill was a predictor of social function in both of these population. Given that differences in sensorimotor integration, as highlighted during this thesis, and a potential autism specific sensorimotor system (J. Cook, 2016; Mostofsky & Ewen, 2011) have been suggested to influence motor execution and the perception and prediction of others during social interaction (J. Cook, 2016) it could be of interest for future research to include volunteers with a DCD, but not an autism, diagnosis. This would allow for further investigation into this overlap of difficulties (Sumner et al., 2016) and provide an opportunity to examine whether the observed differences in feedforward sensorimotor control processes evidenced in this body of work do indeed relate to a potential autism specific sensorimotor system (J. Cook, 2016; Mostofsky & Ewen, 2011), or whether the findings of this thesis may be associated with more general sensorimotor differences present in both diagnoses.

6.5 Conclusion

Since the first study of imitation in autism by DeMyer and colleagues (1972), interest in the area has grown dramatically as it closely relates to the social and communicative difficulties experienced by autistic individuals. Although imitation

has been shown to develop from a young age in typical developing individuals (Oostenbroek et al., 2016), many studies have shown imitation differences in autism (for a review see Edwards, 2014; Vivanti & Hamilton, 2014). Of relevance to the current thesis are studies which have suggested there to be a specific difficulty in the imitation of the lower-level biological kinematic properties of an observed action (DeMyer et al., 1972; Hayes et al., 2016; R. P. Hobson & Lee, 1999; Rogers et al., 1996; Stewart et al., 2013; Wild et al., 2012). During imitation the action observation network allows a visual input to be processed and mapped to a motor output, however the aforementioned differences in imitation are unlikely to be associated with this aspect of sensorimotor processing as investigations into automatic imitation have shown this to be operational (Bird et al., 2007; Edey et al., 2016; Hamilton et al., 2007; Press et al., 2010; Schulte-Rüther et al., 2017; Sowden et al., 2016; Spengler, Bird, et al., 2010). Consequently, associated sensorimotor processes (Hamilton, 2013; Leighton, Bird, Charman, & Heyes, 2008) that complement the encoding of biological motion during imitation may contribute to the observed differences in imitation. This thesis therefore examined sensorimotor integration across the contexts of motor learning, imitation and observational practice to better understand its role in imitation in autism spectrum disorders. Findings showed that across all three contexts autistic individuals are able to successfully form new internal action models (Gidley Larson et al., 2008; Hayes et al., 2018), that represent the sensory consequences of a given action (Krakauer & Shadmehr, 2007), however the effectiveness of this processing and resultant motor execution is potentially modulated by specificity in the autistic sensorimotor system (Cook, 2016; Mostofsky & Ewen, 2011). For example, in *Chapter Three* it was found that the movements produced by the autism group were generally longer and more variable than those of controls. It is possible that these differences are related to a potential strategy

whereby slower movements are produced by autistic individuals so that sensory feedback can be used to overcome autism specific issues in forming an inverse model (i.e., state estimation and/or planning) and feedforward control (Elliott et al., 2010). Similarly, *Chapter Five* showed that although control and autistic participants both successfully formed new internal action models following observational practice, where there was no active contribution of the peripheral motor system, when reafference was introduced this was processed less effectively in autism. Together these findings highlight differences in sensorimotor integration in autism and how this may relate to the aforementioned difficulties in voluntary imitation. However, it is important to note that the findings from *Chapter Four* do show that issues related to sensorimotor processing and integration may be modulated by structuring the imitation environment in a predictable manner such that it facilitates trial-to-trial sensorimotor processing, integration and encoding of *atypical* biological motion.

7 References

Allen, G., Müller, R.-A., & Courchesne, E. (2004). Cerebellar function in autism: functional magnetic resonance image activation during a simple motor task. *Biological Psychiatry, 56*(4), 269-278.

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

Andrew, M., Bennett, S. J., Elliott, D., & Hayes, S. J. (2016). Complimentary lower-level and higher-order systems underpin imitation learning. *Brain and Cognition, 104*, 25-33.

Asperger, H. (1944). Autistic psychopathy in childhood. *European Archives of Psychiatry and Clinical Neuroscience, 117*(1), 76-136.

American Psychiatric Association. (1980). Diagnostic and statistical manual of mental disorders; (DSM-III). *Washington DC*.

American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders: DSM-IV*. Washington DC: American Psychiatric Association.

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

Baio, J., Wiggins, L., Christensen, D. L., Maenner, M. J., Daniels, J., Warren, Z., . . . White, T. (2018). Prevalence of Autism Spectrum Disorder Among Children Aged 8 Years—Autism and Developmental Disabilities Monitoring Network, 11 Sites, United States, 2014. *MMWR Surveillance Summaries, 67*(6), 1.

Baranek, G. T. (1999). Autism during infancy: A retrospective video analysis of sensory-motor and social behaviors at 9–12 months of age. *Journal of Autism and Developmental Disorders, 29*(3), 213-224.

Baron-Cohen, S., Leslie, A. M., & Frith, U. (1985). Does the autistic child have a "theory of mind"? *Cognition, 21*(1), 37-46.

Baron-Cohen, S. (1989). The autistic child's theory of mind: A case of specific developmental delay. *Journal of Child Psychology and Psychiatry, 30*(2), 285-297.

Baum, S. H., Stevenson, R. A., & Wallace, M. T. (2015). Behavioral, perceptual, and neural alterations in sensory and multisensory function in autism spectrum disorder. *Progress in Neurobiology, 134*, 140-160.

Bauminger, N., & Kasari, C. (2000). Loneliness and friendship in high-functioning children with autism. *Child Development, 71*(2), 447-456.

Bekkering, H., Wohlschlager, A., & Gattis, M. (2000). Imitation of gestures in children is goal-directed. *The Quarterly Journal of Experimental Psychology: Section A, 53*(1), 153-164.

Bennett, S. J., & Barnes, G. R. (2003). Human ocular pursuit during the transient disappearance of a visual target. *Journal of Neurophysiology, 90*(4), 2504-2520. doi:10.1152/jn.01145.2002

Bernier, R., Dawson, G., Webb, S., & Murias, M. (2007). EEG mu rhythm and imitation impairments in individuals with autism spectrum disorder. *Brain and Cognition, 64*(3), 228-237.

Bertenthal, B. I., Longo, M. R., & Kosobud, A. (2006). Imitative response tendencies following observation of intransitive actions. *Journal of Experimental Psychology: Human Perception and Performance, 32*(2), 210.

Bhat, A. N., Landa, R. J., & Galloway, J. C. (2011). Current perspectives on motor functioning in infants, children, and adults with autism spectrum disorders. *Physical Therapy, 91*(7), 1116-1129.

Bird, G., & Heyes, C. (2005). Effector-dependent learning by observation of a finger movement sequence. *Journal of Experimental Psychology: Human Perception and Performance, 31*(2), 262.

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

Bird, G., Osman, M., Saggerson, A., & Heyes, C. (2005). Sequence learning by action, observation and action observation. *British Journal of Psychology, 96*(3), 371-388.

Bizzi, E., Tresch, M. C., Saltiel, P., & d'Avella, A. (2000). New perspectives on spinal motor systems. *Nature Reviews Neuroscience, 1*(2), 101.

Blakemore, S.-J., & Frith, C. (2005). The role of motor contagion in the prediction of action. *Neuropsychologia, 43*(2), 260-267.

Blakemore, S.-J., Frith, C. D., & Wolpert, D. M. (1999). Spatio-temporal prediction modulates the perception of self-produced stimuli. *Journal of Cognitive Neuroscience, 11*(5), 551-559.

Blakemore, S.-J., Tavassoli, T., Calò, S., Thomas, R. M., Catmur, C., Frith, U., & Haggard, P. (2006). Tactile sensitivity in Asperger syndrome. *Brain and Cognition, 61*(1), 5-13.

Blandin, Y., & Proteau, L. (2000). On the cognitive basis of observational learning: Development of mechanisms for the detection and correction of errors. *The Quarterly Journal of Experimental Psychology: Section A, 53*(3), 846-867.

Boucher, J. (2012). Putting theory of mind in its place: psychological explanations of the socio-emotional-communicative impairments in autistic spectrum disorder. *Autism, 16*(3), 226-246.

Brass, M., Bekkering, H., & Prinz, W. (2001). Movement observation affects movement execution in a simple response task. *Acta Psychologica, 106*(1), 3-22.

Brass, M., & Heyes, C. (2005). Imitation: is cognitive neuroscience solving the correspondence problem? *Trends in Cognitive Sciences, 9*(10), 489-495.

Brewer, R., Biotti, F., Catmur, C., Press, C., Happé, F., Cook, R., & Bird, G. (2016). Can neurotypical individuals read autistic facial expressions? Atypical production of emotional facial expressions in autism spectrum disorders. *Autism Research, 9*(2), 262-271.

Brown, C., & Dunn, W. (2002). *Adolescent-adult sensory profile: user's manual*: Therapy Skill Builders San Antonio.

Buccino, G., Vogt, S., Ritzl, A., Fink, G. R., Zilles, K., Freund, H.-J., & Rizzolatti, G. (2004). Neural circuits underlying imitation learning of hand actions: an event-related fMRI study. *Neuron, 42*(2), 323-334.

Calhoun, M., Longworth, M., & Chester, V. L. (2011). Gait patterns in children with autism. *Clinical Biomechanics, 26*(2), 200-206.

Candidi, M., Urgesi, C., Ionta, S., & Aglioti, S. M. (2008). Virtual lesion of ventral premotor cortex impairs visual perception of biomechanically possible but not impossible actions. *Social Neuroscience, 3*(3-4), 388-400.

Carmo, J. C., Rumiati, R. I., Siugzdaite, R., & Brambilla, P. (2013). Preserved imitation of known gestures in children with high-functioning autism. *ISRN Neurology, 2013*.

Carpendale, J. I., & Lewis, C. (2004). Constructing an understanding of mind: The development of children's social understanding within social interaction. *Behavioral and Brain Sciences, 27*(1), 79-96.

Carpenter, M., Akhtar, N., & Tomasello, M. (1998). Fourteen-through 18-month-old infants differentially imitate intentional and accidental actions. *Infant Behavior and Development, 21*(2), 315-330.

Carter, A., Davis, N. O., Klin, A., & Volkmar, F. (2005). Social Development in Autism. In F. Volkmar, A. Klin, & D. Cohen (Eds.), *Handbook of Autism and Pervasive Developmental Disorders: Diagnosis, development, neurobiology, and behavior* (pp. 312-334). Hoboken, NJ: John Wiley & Sons Inc.

Cascio, C. J., Foss-Feig, J. H., Burnette, C. P., Heacock, J. L., & Cosby, A. A. (2012). The rubber hand illusion in children with autism spectrum disorders: delayed influence of combined tactile and visual input on proprioception. *Autism, 16*(4), 406-419.

Casile, A., & Giese, M. A. (2006). Nonvisual motor training influences biological motion perception. *Current Biology, 16*(1), 69-74.

Catmur, C., & Heyes, C. (2011). Time course analyses confirm independence of imitative and spatial compatibility. *Journal of Experimental Psychology: Human Perception and Performance, 37*(2), 409.

Catmur, C., Walsh, V., & Heyes, C. (2007). Sensorimotor learning configures the human mirror system. *Current Biology, 17*(17), 1527-1531.

Cattaneo, L., Fabbri-Destro, M., Boria, S., Pieraccini, C., Monti, A., Cossu, G., & Rizzolatti, G. (2007). Impairment of actions chains in autism and its possible role in intention understanding. *Proceedings of the National Academy of Sciences, 104*(45), 17825-17830.

Chung, Y. S., Barch, D., & Strube, M. (2013). A meta-analysis of mentalizing impairments in adults with schizophrenia and autism spectrum disorder. *Schizophrenia Bulletin, 40*(3), 602-616.

Cohen, R. G., & Rosenbaum, D. A. (2004). Where grasps are made reveals how grasps are planned: generation and recall of motor plans. *Experimental Brain Research, 157*(4), 486-495.

Cook, J. (2016). From movement kinematics to social cognition: the case of autism. *Phil. Trans. R. Soc. B, 371*(1693), 20150372.

Cook, J., Blakemore, S.-J., & Press, C. (2013). Atypical basic movement kinematics in autism spectrum conditions. *Brain, 136*(9), 2816-2824. doi:10.1093/brain/awt208

Cook, J., Saygin, A. P., Swain, R., & Blakemore, S.-J. (2009). Reduced sensitivity to minimum-jerk biological motion in autism spectrum conditions. *Neuropsychologia, 47*(14), 3275-3278. doi:http://dx.doi.org/10.1016/j.neuropsychologia.2009.07.010

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

Cook, R., Bird, G., Catmur, C., Press, C., & Heyes, C. (2014). Mirror neurons: from origin to function. *Behavioral and Brain Sciences, 37*(02), 177-192.

Courchesne, E., Press, G., & Yeung-Courchesne, R. (1993). Parietal lobe abnormalities detected with MR in patients with infantile autism. *AJR. American Journal of Roentgenology, 160*(2), 387-393.

Courchesne, E., Townsend, J., Akshoomoff, N. A., Saitoh, O., Yeung-Courchesne, R., Lincoln, A. J., . . . Lau, L. (1994). Impairment in shifting attention in autistic and cerebellar patients. *Behavioral Neuroscience, 108*(5), 848.

Crane, L., Goddard, L., & Pring, L. (2009). Sensory processing in adults with autism spectrum disorders. *Autism, 13*(3), 215-228.

Cross, E. S., Kraemer, D. J., Hamilton, A. F. d. C., Kelley, W. M., & Grafton, S. T. (2009). Sensitivity of the action observation network to physical and observational learning. *Cerebral Cortex, 19*(2), 315-326.

Cummins, A., Piek, J. P., & Dyck, M. J. (2005). Motor coordination, empathy, and social behaviour in school-aged children. *Developmental Medicine and Child Neurology, 47*(7), 437-442.

Cusack, J. P., Williams, J. H., & Neri, P. (2015). Action perception is intact in autism spectrum disorder. *Journal of Neuroscience, 35*(5), 1849-1857.

Dapretto, M., Davies, M. S., Pfeifer, J. H., Scott, A. A., Sigman, M., Bookheimer, S. Y., & Iacoboni, M. (2006). Understanding emotions in others: mirror neuron dysfunction in children with autism spectrum disorders. *Nature Neuroscience, 9*(1), 28-30.

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

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

Dawson, G., Meltzoff, A. N., Osterling, J., Rinaldi, J., & Brown, E. (1998). Children with autism fail to orient to naturally occurring social stimuli. *Journal of Autism and Developmental Disorders, 28*(6), 479-485.

DeMyer, M., Alpern, G., Barton, S., DeMyer, W., Churchill, D., Hingtgen, J., . . . Kimberlin, C. (1972). Imitation in autistic, early schizophrenic, and non-

psychotic subnormal children. *Journal of Autism and Childhood Schizophrenia, 2*(3), 264-287. doi:10.1007/BF01537618

Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences, 4*(11), 423-431.

Dewey, D., Kaplan, B. J., Crawford, S. G., & Wilson, B. N. (2002). Developmental coordination disorder: associated problems in attention, learning, and psychosocial adjustment. *Human movement science, 21*(5-6), 905-918.

Doyon, J., Bellec, P., Amsel, R., Penhune, V., Monchi, O., Carrier, J., . . . Benali, H. (2009). Contributions of the basal ganglia and functionally related brain structures to motor learning. *Behavioural Brain Research, 199*(1), 61-75.

Edey, R., Cook, J., Brewer, R., Johnson, M. H., Bird, G., & Press, C. (2016). Interaction takes two: Typical adults exhibit mind-blindness towards those with autism spectrum disorder. *Journal of Abnormal Psychology, 125*(7), 879.

Eliassen, J. C., Souza, T., & Sanes, J. N. (2001). Human brain activation accompanying explicitly directed movement sequence learning. *Experimental Brain Research, 141*(3), 269-280.

Elliott, D., Hansen, S., Grierson, L. E. M., Lyons, J., Bennett, S. J., & Hayes, S. J. (2010). Goal-directed aiming: Two components but multiple processes. *Psychological Bulletin, 136*(6), 1023-1044. doi:10.1037/a0020958

Elliott, D., Helsen, W. F., & Chua, R. (2001). A century later: Woodworth's (1899) two-component model of goal-directed aiming. *Psychological Bulletin, 127*(3), 342.

Fabbri-Destro, M., Cattaneo, L., Boria, S., & Rizzolatti, G. (2009). Planning actions in autism. *Experimental Brain Research, 192*(3), 521-525.

Flash, T., & Hogan, N. (1985). The coordination of arm movements: an experimentally confirmed mathematical model. *The Journal of Neuroscience, 5*(7), 1688-1703.

Foss-Feig, J. H., Kwakye, L. D., Cascio, C. J., Burnette, C. P., Kadivar, H., Stone, W. L., & Wallace, M. T. (2010). An extended multisensory temporal binding window in autism spectrum disorders. *Experimental Brain Research, 203*(2), 381-389.

Fournier, K., Hass, C., Naik, S., Lodha, N., & Cauraugh, J. (2010). Motor Coordination in Autism Spectrum Disorders: A Synthesis and Meta-Analysis. *Journal of Autism and Developmental Disorders, 40*(10), 1227-1240. doi:10.1007/s10803-010-0981-3

Frith, U., & Happé, F. (1994). Autism: Beyond "theory of mind". *Cognition, 50*(1), 115-132.

Frith, U., & Happé, F. (2005). Autism spectrum disorder. *Current Biology, 15*(19), R786-R790.

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

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

Ghez, C., Hening, W., & Gordon, J. (1991). Organization of voluntary movement. *Current Opinion in Neurobiology, 1*(4), 664-671.

Gidley Larson, J. C., Bastian, A. J., Donchin, O., Shadmehr, R., & Mostofsky, S. H. (2008). Acquisition of internal models of motor tasks in children with autism. *Brain, 131*(11), 2894-2903.

Glazebrook, C. M., Elliott, D., & Lyons, J. (2006). A kinematic analysis of how young adults with and without autism plan and control goal-directed movements. *MOTOR CONTROL-CHAMPAIGN-, 10*(3), 244.

Glazebrook, C. M., Elliott, D., & Szatmari, P. (2008). How do individuals with autism plan their movements? *Journal of Autism and Developmental Disorders, 38*(1), 114-126.

Glazebrook, C. M., Gonzalez, D., Hansen, S., & Elliott, D. (2009). The role of vision for online control of manual aiming movements in persons with autism spectrum disorders. *Autism, 13*(4), 411-433.

Gowen, E., & Hamilton, A. F. d. C. (2013). Motor abilities in autism: a review using a computational context. *Journal of Autism and Developmental Disorders, 43*(2), 323-344.

Gowen, E., Stanley, J., & Miall, R. (2008). Movement interference in autism-spectrum disorder. *Neuropsychologia, 46*(4), 1060-1068.

Green, D., Baird, G., Barnett, A. L., Henderson, L., Huber, J., & Henderson, S. E. (2002). The severity and nature of motor impairment in Asperger's syndrome: a comparison with specific developmental disorder of motor function. *Journal of Child Psychology and Psychiatry, 43*(5), 655-668.

Green, D., Charman, T., Pickles, A., Chandler, S., Loucas, T., Simonoff, E., & Baird, G. (2009). Impairment in movement skills of children with autistic spectrum disorders. *Developmental Medicine & Child Neurology, 51*(4), 311-316.

Hagberg, K. W., & Jick, H. (2010). Autism in the UK for birth cohorts 1988–2001. *Epidemiology, 21*(3), 426-427.

Hamilton, A. F. d. C. (2013). Reflecting on the mirror neuron system in autism: a systematic review of current theories. *Developmental Cognitive Neuroscience, 3*, 91-105.

Hamilton, A. F. d. C. (2015). The neurocognitive mechanisms of imitation. *Current Opinion in Behavioral Sciences, 3*(0), 63-67. doi:http://dx.doi.org/10.1016/j.cobeha.2015.01.011

Hamilton, A. F. d. C., Brindley, R. M., & Frith, U. (2007). Imitation and action understanding in autistic spectrum disorders: how valid is the hypothesis of a deficit in the mirror neuron system? *Neuropsychologia, 45*(8), 1859-1868. doi:10.1016/j.neuropsychologia.2006.11.022

Happé, F. (1995). The role of age and verbal ability in the theory of mind task performance of subjects with autism. *Child Development, 66*(3), 843-855.

Happé, F., & Frith, U. (2006). The weak coherence account: detail-focused cognitive style in autism spectrum disorders. *Journal of Autism and Developmental Disorders, 36*(1), 5-25.

Happé, F., Ronald, A., & Plomin, R. (2006). Time to give up on a single explanation for autism. *Nature Neuroscience, 9*(10), 1218.

Hardwick, R. M., & Edwards, M. G. (2012). Motor interference and facilitation arising from observed movement kinematics. *The Quarterly Journal of Experimental Psychology, 65*(5), 840-847.

Harms, M. B., Martin, A., & Wallace, G. L. (2010). Facial emotion recognition in autism spectrum disorders: a review of behavioral and neuroimaging studies. *Neuropsychology Review, 20*(3), 290-322.

Harris, J. (2018). Leo Kanner and autism: a 75-year perspective. *International Review of Psychiatry*, 1-15.

Haswell, C. C., Izawa, J., Dowell, L. R., Mostofsky, S. H., & Shadmehr, R. (2009). Representation of internal models of action in the autistic brain. *Nature Neuroscience, 12*(8), 970-972.

Hayes, S. J., Andrew, M., Elliott, D., Gowen, E., & Bennett, S. J. (2016). Low Fidelity Imitation of Atypical Biological Kinematics in Autism Spectrum Disorders Is Modulated by Self-Generated Selective Attention. *Journal of Autism and Developmental Disorders, 46*(2), 502-513. doi:10.1007/s10803-015-2588-1

Hayes, S. J., Andrew, M., Elliott, D., Roberts, J. W., & Bennett, S. J. (2012). Dissociable contributions of motor-execution and action-observation to intermanual transfer. *Neuroscience Letters, 506*(2), 346-350.

Hayes, S. J., Andrew, M., Foster, N. C., Elliott, D., Gowen, E., & Bennett, S. J. (2018). Sensorimotor learning and associated visual perception are intact but unrelated in autism spectrum disorder. *Autism Research, 11*(2), 296-304.

Hayes, S. J., Dutoy, C. A., Elliott, D., Gowen, E., & Bennett, S. J. (2016). Atypical biological motion kinematics are represented by complementary lower-level and top-down processes during imitation learning. *Acta Psychologica, 163*, 10-16.

Hayes, S. J., Elliott, D., & Bennett, S. J. (2010). General motor representations are developed during action-observation. *Experimental Brain Research, 204*(2), 199-206.

Hayes, S. J., Elliott, D., & Bennett, S. J. (2013). Visual online control processes are acquired during observational practice. *Acta Psychologica, 143*(3), 298-302. doi:dx.doi.org/10.1016/j.actpsy.2013.04.012

Hayes, S. J., Roberts, J. W., Elliott, D., & Bennett, S. J. (2014). Top-Down Attentional Processes Modulate the Coding of Atypical Biological Motion

Kinematics in the Absence of Motor Signals. *Journal of Experimental Psychology: Human Perception and Performance, 40*(4), 1641-1653.

Hayes, S. J., Timmis, M. A., & Bennett, S. J. (2009). Eye movements are not a prerequisite for learning movement sequence timing through observation. *Acta Psychologica, 131*(3), 202-208.

Hendricks, D. (2010). Employment and adults with autism spectrum disorders: Challenges and strategies for success. *Journal of Vocational Rehabilitation, 32*(2), 125-134.

Heuer, H., & Schmidt, R. A. (1988). Transfer of learning among motor patterns with different relative timing. *Journal of Experimental Psychology: Human Perception and Performance, 14*(2), 241.

Heyes, C. (2001). Causes and consequences of imitation. *Trends in Cognitive Sciences, 5*(6), 253-261.

Heyes, C. (2011). Automatic imitation. *Psychological Bulletin, 137*(3), 463.

Heyes, C., Bird, G., Johnson, H., & Haggard, P. (2005). Experience modulates automatic imitation. *Cognitive Brain Research, 22*(2), 233-240.

Hobson, R. P., & Lee, A. (1999). Imitation and identification in autism. *Journal of Child Psychology and Psychiatry, 40*(04), 649-659.

Hommel, B., & Lippa, Y. (1995). SR compatibility effects due to context-dependent spatial stimulus coding. *Psychonomic Bulletin & Review, 2*(3), 370-374.

Hughes, C. (1996). Brief report: Planning problems in autism at the level of motor control. *Journal of Autism and Developmental Disorders, 26*(1), 99-107.

Iacoboni, M., Woods, R. P., Brass, M., Bekkering, H., Mazziotta, J. C., & Rizzolatti, G. (1999). Cortical mechanisms of human imitation. *Science, 286*(5449), 2526-2528.

Izawa, J., Pekny, S. E., Marko, M. K., Haswell, C. C., Shadmehr, R., & Mostofsky, S. H. (2012). Motor Learning Relies on Integrated Sensory Inputs in ADHD, but Over-Selectively on Proprioception in Autism Spectrum Conditions. *Autism Research, 5*(2), 124-136. doi:10.1002/aur.1222

Jarosz, A. F., & Wiley, J. (2014). What are the odds? A practical guide to computing and reporting Bayes factors. *The Journal of Problem Solving, 7*(1), 2.

Jeannerod, M. (1994). The representing brain: Neural correlates of motor intention and imagery. *Behavioral and Brain Sciences, 17*(2), 187-202.

Jeannerod, M. (2001). Neural simulation of action: a unifying mechanism for motor cognition. *NeuroImage, 14*(1), S103-S109.

Jones, C. R., Simonoff, E., Baird, G., Pickles, A., Marsden, A. J., Tregay, J., . . . Charman, T. (2018). The association between theory of mind, executive function, and the symptoms of autism spectrum disorder. *Autism Research, 11*(1), 95-109.

Kanner, L. (1943). Autistic disturbances of affective contact. *Nervous Child, 2*(3), 217-250.

Kanner, L. (1971). Follow-up study of eleven autistic children originally reported in 1943. *Journal of Autism and Childhood Schizophrenia, 1*(2), 119-145.

Kantak, S. S., & Winstein, C. J. (2012). Learning–performance distinction and memory processes for motor skills: A focused review and perspective. *Behavioural Brain Research, 228*(1), 219-231.

Khan, M. A., Elliott, D., Coull, J., Chua, R., & Lyons, J. (2002). Optimal control strategies under different feedback schedules: Kinematic evidence. *Journal of Motor Behavior, 34*(1), 45-57.

Kilner, J. M., Hamilton, A. F. d. C., & Blakemore, S.-J. (2007). Interference effect of observed human movement on action is due to velocity profile of biological

motion. *Social Neuroscience, 2*(3-4), 158-166. doi:10.1080/17470910701428190

Kilner, J. M., Paulignan, Y., & Blakemore, S. J. (2003). An Interference Effect of Observed Biological Movement on Action. *Current Biology, 13*(6), 522-525. doi:http://dx.doi.org/10.1016/S0960-9822(03)00165-9

Klin, A., Lin, D. J., Gorrindo, P., Ramsay, G., & Jones, W. (2009). Two-year-olds with autism orient to non-social contingencies rather than biological motion. *Nature, 459*(7244), 257-261.

Klin, A., Sparrow, S. S., De Bildt, A., Cicchetti, D. V., Cohen, D. J., & Volkmar, F. R. (1999). A normed study of face recognition in autism and related disorders. *Journal of Autism and Developmental Disorders, 29*(6), 499-508.

Kolvin, I. (1971). Studies in the childhood psychoses I. Diagnostic criteria and classification. *The British Journal of Psychiatry, 118*(545), 381-384.

Krakauer, J. W., & Shadmehr, R. (2007). Towards a computational neuropsychology of action. *Progress in Brain Research, 165*, 383-394.

Kwakye, L. D., Foss-Feig, J. H., Cascio, C. J., Stone, W. L., & Wallace, M. T. (2011). Altered auditory and multisensory temporal processing in autism spectrum disorders. *Frontiers in Integrative Neuroscience, 4*, 129.

Lam, K. S., & Aman, M. G. (2007). The Repetitive Behavior Scale-Revised: independent validation in individuals with autism spectrum disorders. *Journal of Autism and Developmental Disorders, 37*(5), 855-866.

Leary, M. R., & Hill, D. A. (1996). Moving on: autism and movement disturbance. *Mental Retardation, 34*(1), 39.

Legare, C. H., & Nielsen, M. (2015). Imitation and innovation: The dual engines of cultural learning. *Trends in Cognitive Sciences, 19*(11), 688-699.

Leighton, J., Bird, G., Charman, T., & Heyes, C. (2008). Weak imitative performance is not due to a functional 'mirroring'deficit in adults with Autism Spectrum Disorders. *Neuropsychologia, 46*(4), 1041-1049.

Li, B., Sharma, A., Meng, J., Purushwalkam, S., & Gowen, E. (2017). Applying machine learning to identify autistic adults using imitation: An exploratory study. *PloS One, 12*(8), e0182652.

Lindner, J. L., & Rosén, L. A. (2006). Decoding of emotion through facial expression, prosody and verbal content in children and adolescents with Asperger's syndrome. *Journal of Autism and Developmental Disorders, 36*(6), 769-777.

Lopez, B. R., Lincoln, A. J., Ozonoff, S., & Lai, Z. (2005). Examining the relationship between executive functions and restricted, repetitive symptoms of autistic disorder. *Journal of Autism and Developmental Disorders, 35*(4), 445-460.

Lord, C., Pickles, A., Dilavore, P., & Shulman, C. (1996). *Longitudinal studies of young children referred for possible autism.* Paper presented at the biannual meetings of the International Society for Research in Child and Adolescent Psychopathology.

Lord, C., Risi, S., Lambrecht, L., Cook, E., Jr., Leventhal, B., DiLavore, P., . . . Rutter, M. (2000). The Autism Diagnostic Observation Schedule—Generic: A Standard Measure of Social and Communication Deficits Associated with the Spectrum of Autism. *Journal of Autism and Developmental Disorders, 30*(3), 205-223. doi:10.1023/A:1005592401947

Lord, C., Rutter, M., DiLavore, P., Risi, S., Gotham, K., & Bishop, S. (2012). *Autism diagnostic observation schedule: ADOS-2*: Western Psychological Services Torrance.

Lord, C., Shulman, C., & DiLavore, P. (2004). Regression and word loss in autistic spectrum disorders. *Journal of Child Psychology and Psychiatry, 45*(5), 936-955.

Losh, M., Sullivan, P. F., Trembath, D., & Piven, J. (2008). Current developments in the genetics of autism: from phenome to genome. *Journal of Neuropathology & Experimental Neurology, 67*(9), 829-837.

Lovaas, I., Newsom, C., & Hickman, C. (1987). Self-stimulatory behavior and perceptual reinforcement. *Journal of Applied Behavior Analysis, 20*(1), 45-68.

Machado, S., Cunha, M., Velasques, B., Minc, D., Teixeira, S., Domingues, C. A., . . . Cagy, M. (2010). Sensorimotor integration: basic concepts, abnormalities related to movement disorders and sensorimotor training-induced cortical reorganization. *Rev Neurol, 51*(7), 427-436.

Mari, M., Castiello, U., Marks, D., Marraffa, C., & Prior, M. (2003). The reach–to–grasp movement in children with autism spectrum disorder. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 358*(1430), 393-403.

Marko, M. K., Crocetti, D., Hulst, T., Donchin, O., Shadmehr, R., & Mostofsky, S. H. (2015). Behavioural and neural basis of anomalous motor learning in children with autism. *Brain*, 394.

Masson, M. E. (2011). A tutorial on a practical Bayesian alternative to null-hypothesis significance testing. *Behavior Research Methods, 43*(3), 679-690.

Maurer, R. G., & Damasio, A. R. (1982). Childhood autism from the point of view of behavioral neurology. *Journal of Autism and Developmental Disorders, 12*(2), 195-205.

Meltzoff, A. N., & Moore, M. K. (1997). Explaining facial imitation: A theoretical model. *Infant and Child Development, 6*(3-4), 179-192.

Miall, R. C., & Wolpert, D. M. (1996). Forward models for physiological motor control. *Neural Networks, 9*(8), 1265-1279.

Mitchell, S., Brian, J., Zwaigenbaum, L., Roberts, W., Szatmari, P., Smith, I., & Bryson, S. (2006). Early language and communication development of infants later diagnosed with autism spectrum disorder. *Journal of Developmental & Behavioral Pediatrics, 27*(2), S69-S78.

Molinari, M., Restuccia, D., & Leggio, M. G. (2009). State estimation, response prediction, and cerebellar sensory processing for behavioral control. *The Cerebellum, 8*(3), 399-402.

Monfils, M.-H., Plautz, E. J., & Kleim, J. A. (2005). In search of the motor engram: motor map plasticity as a mechanism for encoding motor experience. *The Neuroscientist, 11*(5), 471-483.

Morey, R. D., & Rouder, J. N. (2015). BayesFactor: Computation of Bayes factors for common designs. R package version 0.9.12-2. *https://CRAN.R-project.org/package=BayesFactor*.

Mosconi, M. W., Mohanty, S., Greene, R. K., Cook, E. H., Vaillancourt, D. E., & Sweeney, J. A. (2015). Feedforward and feedback motor control abnormalities implicate cerebellar dysfunctions in autism spectrum disorder. *The Journal of Neuroscience, 35*(5).

Mostofsky, S. H., Dubey, P., Jerath, V. K., Jansiewicz, E. M., Goldberg, M. C., & Denckla, M. B. (2006). Developmental dyspraxia is not limited to imitation in children with autism spectrum disorders. *Journal of the International Neuropsychological Society, 12*(03), 314-326.

Mostofsky, S. H., & Ewen, J. B. (2011). Altered connectivity and action model formation in autism is autism. *The Neuroscientist, 17*(4), 437-448.

Mostofsky, S. H., Goldberg, M. C., Landa, R. J., & Denckla, M. B. (2000). Evidence for a deficit in procedural learning in children and adolescents with autism: implications for cerebellar contribution. *Journal of the International Neuropsychological Society, 6*(07), 752-759.

Müller, R.-A., Cauich, C., Rubio, M. A., Mizuno, A., & Courchesne, E. (2004). Abnormal activity patterns in premotor cortex during sequence learning in autistic patients. *Biological Psychiatry, 56*(5), 323-332.

Müller, R.-A., Kleinhans, N., Kemmotsu, N., Pierce, K., & Courchesne, E. (2003). Abnormal variability and distribution of functional maps in autism: an FMRI study of visuomotor learning. *American Journal of Psychiatry, 160*(10), 1847-1862.

Nackaerts, E., Wagemans, J., Helsen, W., Swinnen, S. P., Wenderoth, N., & Alaerts, K. (2012). Recognizing biological motion and emotions from point-light displays in autism spectrum disorders. *PloS One, 7*(9), e44473.

Nazarali, N., Glazebrook, C. M., & Elliott, D. (2009). Movement planning and reprogramming in individuals with autism. *Journal of Autism and Developmental Disorders, 39*(10), 1401-1411.

Nebel, M. B., Eloyan, A., Nettles, C. A., Sweeney, K. L., Ament, K., Ward, R. E., . . . Mostofsky, S. H. (2016). Intrinsic visual-motor synchrony correlates with social deficits in autism. *Biological Psychiatry, 79*(8), 633-641.

O'Riordan, M., & Plaisted, K. (2001). Enhanced discrimination in autism. *The Quarterly Journal of Experimental Psychology: Section A, 54*(4), 961-979.

Oberman, L. M., Hubbard, E. M., McCleery, J. P., Altschuler, E. L., Ramachandran, V. S., & Pineda, J. A. (2005). EEG evidence for mirror neuron dysfunction in autism spectrum disorders. *Cognitive Brain Research, 24*(2), 190-198.

Oostenbroek, J., Suddendorf, T., Nielsen, M., Redshaw, J., Kennedy-Costantini, S., Davis, J., . . . Slaughter, V. (2016). Comprehensive longitudinal study challenges the existence of neonatal imitation in humans. *Current Biology, 26*(10), 1334-1338.

Osman, M., Bird, G., & Heyes, C. (2005). Action observation supports effector-dependent learning of finger movement sequences. *Experimental Brain Research, 165*(1), 19-27.

Ozonoff, S., Young, G. S., Carter, A., Messinger, D., Yirmiya, N., Zwaigenbaum, L., . . . Dobkins, K. (2011). Recurrence risk for autism spectrum disorders: a Baby Siblings Research Consortium study. *Pediatrics, 128*(3), e488-e495.

Peterson, C. C., Garnett, M., Kelly, A., & Attwood, T. (2009). Everyday social and conversation applications of theory-of-mind understanding by children with autism-spectrum disorders or typical development. *European Child & Adolescent Psychiatry, 18*(2), 105-115.

Plaisted, K., O'Riordan, M., & Baron-Cohen, S. (1998). Enhanced discrimination of novel, highly similar stimuli by adults with autism during a perceptual learning task. *Journal of Child Psychology and Psychiatry, 39*(5), 765-775.

Premack, D., & Woodruff, G. (1978). Does the chimpanzee have a theory of mind? *Behavioral and Brain Sciences, 1*(4), 515-526.

Press, C. (2011). Action observation and robotic agents: learning and anthropomorphism. *Neuroscience & Biobehavioral Reviews, 35*(6), 1410-1418.

Press, C., Bird, G., Walsh, E., & Heyes, C. (2008). Automatic imitation of intransitive actions. *Brain and Cognition, 67*(1), 44-50.

Press, C., Cook, J., Blakemore, S.-J., & Kilner, J. (2011). Dynamic modulation of human motor activity when observing actions. *Journal of Neuroscience, 31*(8), 2792-2800.

Press, C., Richardson, D., & Bird, G. (2010). Intact imitation of emotional facial actions in autism spectrum conditions. *Neuropsychologia, 48*(11), 3291-3297.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology, 9*(2), 129-154.

Qiu, A., Adler, M., Crocetti, D., Miller, M. I., & Mostofsky, S. H. (2010). Basal ganglia shapes predict social, communication, and motor dysfunctions in boys with autism spectrum disorder. *Journal of the American Academy of Child & Adolescent Psychiatry, 49*(6), 539-551. e534.

Raftery, A. E. (1995). Bayesian model selection in social research. In P. Marsden (Ed.), *Sociological Methodology* (pp. 111-196). Cambridge, MA: Blackwell.

Rinehart, N. J., Bellgrove, M. A., Tonge, B. J., Brereton, A. V., Howells-Rankin, D., & Bradshaw, J. L. (2006). An examination of movement kinematics in young people with high-functioning autism and Asperger's disorder: further evidence for a motor planning deficit. *Journal of Autism and Developmental disorders, 36*(6), 757-767.

Rinehart, N. J., Bradshaw, J. L., Brereton, A. V., & Tonge, B. J. (2001). Movement preparation in high-functioning autism and Asperger disorder: a serial choice reaction time task involving motor reprogramming. *Journal of Autism and Developmental Disorders, 31*(1), 79-88.

Rinehart, N. J., Tonge, B. J., Bradshaw, J. L., Iansek, R., Enticott, P. G., & McGinley, J. (2006). Gait function in high-functioning autism and Asperger's disorder. *European Child & Adolescent Psychiatry, 15*(5), 256-264.

Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. *Annu. Rev. Neurosci., 27*, 169-192.

Rizzolatti, G., & Sinigaglia, C. (2010). The functional role of the parieto-frontal mirror circuit: interpretations and misinterpretations. *Nature Reviews Neuroscience, 11*(4), 264-274.

Roberts, J. W., Bennett, S. J., Elliott, D., & Hayes, S. J. (2015). Motion trajectory information and agency influence motor learning during observational practice. *Acta Psychologica, 159*, 76-84.

Roberts, J. W., Hayes, S. J., Uji, M., & Bennett, S. J. (2014). Motor contagion: the contribution of trajectory and end-points. *Psychological Research*, 1-9.

Rogers, S. J., Bennetto, L., McEvoy, R., & Pennington, B. F. (1996). Imitation and pantomime in high-functioning adolescents with autism spectrum disorders. *Child Development, 67*(5), 2060-2073.

Rogers, S. J., & Pennington, B. F. (1991). A theoretical approach to the deficits in infantile autism. *Development and Psychopathology, 3*(02), 137-162.

Rosenbaum, D. A., & Jorgensen, M. J. (1992). Planning macroscopic aspects of manual control. *Human Movement Science, 11*(1-2), 61-69.

Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J. D., & Jorgensen, M. J. (1990). Constraints for action selection: Overhand versus underhand grips.

Rouder, J. N. (2014). Optional stopping: No problem for Bayesians. *Psychonomic Bulletin & Review, 21*(2), 301-308.

Rumiati, R. I., Weiss, P. H., Tessari, A., Assmus, A., Zilles, K., Herzog, H., & Fink, G. R. (2005). Common and differential neural mechanisms supporting imitation of meaningful and meaningless actions. *Journal of Cognitive Neuroscience, 17*(9), 1420-1431.

Rutter, M. (1978). Diagnosis and definition of childhood autism. *Journal of Autism and Childhood Schizophrenia, 8*(2), 139-161.

Salowitz, N. M., Eccarius, P., Karst, J., Carson, A., Schohl, K., Stevens, S., . . . Scheidt, R. A. (2013). Brief report: visuo-spatial guidance of movement during gesture imitation and mirror drawing in children with autism spectrum disorders. *Journal of Autism and Developmental Disorders, 43*(4), 985-995.

Saunders, J. A., & Knill, D. C. (2005). Humans use continuous visual feedback from the hand to control both the direction and distance of pointing movements. *Experimental Brain Research, 162*(4), 458-473.

Saygin, A. P., Cook, J., & Blakemore, S.-J. (2010). Unaffected perceptual thresholds for biological and non-biological form-from-motion perception in autism spectrum conditions. *PloS One, 5*(10), e13491.

Scheeren, A. M., de Rosnay, M., Koot, H. M., & Begeer, S. (2013). Rethinking theory of mind in high-functioning autism spectrum disorder. *Journal of Child Psychology and Psychiatry, 54*(6), 628-635.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82*(4), 225.

Schmidt, R. A. (1985). The 1984 CH McCloy Research Lecture: The Search for Invariance in Skilled Movement Behavior. *Research Quarterly for Exercise and Sport, 56*(2), 188-200.

Schmitz, C., Martineau, J., Barthélémy, C., & Assaiante, C. (2003). Motor control and children with autism: deficit of anticipatory function? *Neuroscience Letters, 348*(1), 17-20.

Schulte-Rüther, M., Otte, E., Adigüzel, K., Firk, C., Herpertz-Dahlmann, B., Koch, I., & Konrad, K. (2017). Intact mirror mechanisms for automatic facial emotions in children and adolescents with autism spectrum disorder. *Autism Research, 10*(2), 298-310.

Senju, A., & Johnson, M. H. (2009). Atypical eye contact in autism: models, mechanisms and development. *Neuroscience & Biobehavioral Reviews, 33*(8), 1204-1214.

Shadmehr, R., & Krakauer, J. W. (2008). A computational neuroanatomy for motor control. *Experimental Brain Research, 185*(3), 359-381.

Shadmehr, R., & Moussavi, Z. M. (2000). Spatial generalization from learning dynamics of reaching movements. *Journal of Neuroscience, 20*(20), 7807-7815.

Sharer, E., Crocetti, D., Muschelli, J., Barber, A. D., Nebel, M. B., Caffo, B. S., . . . Mostofsky, S. H. (2015). Neural correlates of visuomotor learning in autism. *Journal of Child Neurology, 30*(14), 1877-1886.

Sowden, S., Koehne, S., Catmur, C., Dziobek, I., & Bird, G. (2016). Intact automatic imitation and typical spatial compatibility in autism spectrum disorder: challenging the broken mirror theory. *Autism Research, 9*(2), 292-300.

Spence, C., Pavani, F., Maravita, A., & Holmes, N. (2004). Multisensory contributions to the 3-D representation of visuotactile peripersonal space in humans: evidence from the crossmodal congruency task. *Journal of Physiology-Paris, 98*(1-3), 171-189.

Spengler, S., Bird, G., & Brass, M. (2010). Hyperimitation of actions is related to reduced understanding of others' minds in autism spectrum conditions. *Biological Psychiatry, 68*(12), 1148-1155.

Stanley, J., Gowen, E., & Miall, R. C. (2007). Effects of agency on movement interference during observation of a moving dot stimulus. *Journal of Experimental Psychology: Human Perception and Performance, 33*(4), 915.

Stewart, H. J., McIntosh, R. D., & Williams, J. H. G. (2013). A Specific Deficit of Imitation in Autism Spectrum Disorder. *Autism Research, 6*(6), 522-530. doi:10.1002/aur.1312

Subiaul, F., Lurie, H., Romansky, K., Klein, T., Holmes, D., & Terrace, H. (2007). Cognitive imitation in typically-developing 3-and 4-year olds and individuals with autism. *Cognitive Development, 22*(2), 230-243.

Sumner, E., Leonard, H. C., & Hill, E. L. (2016). Overlapping phenotypes in autism spectrum disorder and developmental coordination disorder: A cross-syndrome comparison of motor and social skills. *Journal of Autism and Developmental Disorders, 46*(8), 2609-2620.

Tager-Flusberg, H. (2000). Language and understanding minds: connections in autism. In S. Baron-Cohen, H. Tager-Flusberg, & D. Cohen (Eds.), *Understanding Other Minds: Perspectives from Developmental Cognitive Neuroscience (2nd Edition)* (pp. 3-46). Oxford, UK: Oxford University Press.

Tager-Flusberg, H., Paul, R., & Lord, C. (2005). Language and communication in autism. In F. Volkmar, A. Klin, & D. Cohen (Eds.), *Handbook of Autism and Pervasive Developmental Disorders: Diagnosis, development, neurobiology, and behavior* (pp. 335-364). Hoboken, NJ: John Wiley & Sons Inc.

Taylor, B., Jick, H., & MacLaughlin, D. (2013). Prevalence and incidence rates of autism in the UK: time trend from 2004–2010 in children aged 8 years. *BMJ open, 3*(10), e003219.

Teitelbaum, P., Teitelbaum, O., Nye, J., Fryman, J., & Maurer, R. G. (1998). Movement analysis in infancy may be useful for early diagnosis of autism. *Proceedings of the National Academy of Sciences, 95*(23), 13982-13987.

Tenenbaum, J. B., Griffiths, T. L., & Kemp, C. (2006). Theory-based Bayesian models of inductive learning and reasoning. *Trends in Cognitive Sciences, 10*(7), 309-318.

Théoret, H., Halligan, E., Kobayashi, M., Fregni, F., Tager-Flusberg, H., & Pascual-Leone, A. (2005). Impaired motor facilitation during action observation in individuals with autism spectrum disorder. *Current Biology, 15*(3), R84-R85.

Travers, B. G., Kana, R. K., Klinger, L. G., Klein, C. L., & Klinger, M. R. (2015). Motor learning in individuals with autism spectrum disorder: activation in superior parietal lobule related to learning and repetitive behaviors. *Autism Research, 8*(1), 38-51.

Turner, M. (1999). Annotation: Repetitive behaviour in autism: A review of psychological research. *The Journal of Child Psychology and Psychiatry and Allied Disciplines, 40*(6), 839-849.

Turnham, E. J., Braun, D. A., & Wolpert, D. M. (2011). Inferring visuomotor priors for sensorimotor learning. *PLoS Computational Biology, 7*(3), e1001112.

van Swieten, L. M., van Bergen, E., Williams, J. H., Wilson, A. D., Plumb, M. S., Kent, S. W., & Mon-Williams, M. A. (2010). A test of motor (not executive) planning in developmental coordination disorder and autism. *Journal of Experimental Psychology: Human Perception and Performance, 36*(2), 493.

Vernazza-Martin, S., Martin, N., Vernazza, A., Lepellec-Muller, A., Rufo, M., Massion, J., & Assaiante, C. (2005). Goal directed locomotion and balance control in autistic children. *Journal of Autism and Developmental Disorders, 35*(1), 91-102.

Vivanti, G., & Hamilton, A. F. d. C. (2014). Imitation in autism spectrum disorders *Handbook of Autism and Pervasive Developmental Disorders, Fourth Edition*.

Vogt, S., Buccino, G., Wohlschläger, A. M., Canessa, N., Shah, N. J., Zilles, K., . . . Fink, G. R. (2007). Prefrontal involvement in imitation learning of hand actions: effects of practice and expertise. *NeuroImage, 37*(4), 1371-1383.

Von Holst, E. (1954). Relations between the central nervous system and the peripheral organs. *British Journal of Animal Behaviour*.

Wagenmakers, E.-J. (2007). A practical solution to the pervasive problems ofp values. *Psychonomic Bulletin & Review, 14*(5), 779-804.

Wang, Z., Magnon, G. C., White, S. P., Greene, R. K., Vaillancourt, D. E., & Mosconi, M. W. (2015). Individuals with autism spectrum disorder show abnormalities during initial and subsequent phases of precision gripping. *Journal of Neurophysiology, 113*(7), 1989-2001.

Wechsler, D. (1999). *Wechsler abbreviated scale of intelligence*: Psychological Corporation.

Weintraub, K. (2011). The prevalence puzzle: autism counts. *Nature News, 479*(7371), 22-24.

White, S. W., Keonig, K., & Scahill, L. (2007). Social skills development in children with autism spectrum disorders: A review of the intervention research. *Journal of Autism and Developmental Disorders, 37*(10), 1858-1868.

Wild, K. S., Poliakoff, E., Jerrison, A., & Gowen, E. (2012). Goal-directed and goal-less imitation in autism spectrum disorder. *Journal of Autism and Developmental Disorders, 42*(8), 1739-1749.

Williams, J. H., Waiter, G. D., Gilchrist, A., Perrett, D. I., Murray, A. D., & Whiten, A. (2006). Neural mechanisms of imitation and 'mirror neuron'functioning in autistic spectrum disorder. *Neuropsychologia, 44*(4), 610-621.

Williams, J. H., Whiten, A., & Singh, T. (2004). A systematic review of action imitation in autistic spectrum disorder. *Journal of Autism and Developmental Disorders, 34*(3), 285-299.

Williams, J. H., Whiten, A., Suddendorf, T., & Perrett, D. I. (2001). Imitation, mirror neurons and autism. *Neuroscience & Biobehavioral Reviews, 25*(4), 287-295.

Wing, L. (1981). Asperger's syndrome: a clinical account. *Psychological Medicine, 11*(1), 115-129.

Wolpert, D. M., Diedrichsen, J., & Flanagan, J. R. (2011). Principles of sensorimotor learning. *Nature Reviews Neuroscience, 12*(12), 739-751.

Wolpert, D. M., & Flanagan, J. R. (2001). Motor prediction. *Current Biology, 11*(18), R729-R732.

Wolpert, D. M., & Flanagan, J. R. (2010). Motor learning. *Current Biology, 20*(11), R467-R472.

Wolpert, D. M., & Ghahramani, Z. (2000). Computational principles of movement neuroscience. *Nature Neuroscience, 3*(11s), 1212.

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science, 269*(5232), 1880-1882.

Wolpert, D. M., & Kawato, M. (1998). Multiple paired forward and inverse models for motor control. *Neural Networks, 11*(7-8), 1317-1329.

Woodworth, R. S. (1899). Accuracy of voluntary movement. *The Psychological Review: Monograph Supplements, 3*(3), i.