Motion Processing in Children with Autism

Catherine Manning

Institute of Education

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Abstract

It has often been reported that individuals with autism process visual motion information atypically. This thesis uses psychophysical methods and a parent-report questionnaire to characterise better the nature of atypical motion processing in children with autism. In Chapter 1, I review the evidence for atypical sensory perception in autism, focusing on the processing of dynamic information. In Chapter 2, I show that children with autism are just as sensitive to speed information as typically developing (TD) children, but have elevated motion coherence thresholds specifically for slow stimuli. In Chapter 3, I analyse questionnaire results which suggest that children with autism have difficulties processing speed-related information in everyday life. In Chapters 4 and 5 I use an equivalent noise direction integration task alongside a standard motion coherence paradigm to determine whether local and/or global factors limit sensitivity to coherent motion information in TD children and children with autism. In Chapter 4, I show that the ability to average motion information drives age-related increases in coherent motion sensitivity in TD children. In Chapter 5, I present the unexpected finding that children with autism have *enhanced* integration of motion information compared to TD children. In an attempt to resolve discrepant motion coherence findings, I reveal that children with autism are equally susceptible to correspondence noise as TD children in Chapter 6. In Chapter 7, I discuss the importance of these findings within the context of current theoretical accounts, and suggest that we need a more nuanced account of motion processing abilities in autism. In particular, I argue that motion processing in autism may be characterised by increased integration and reduced segregation of signal from noise.

Declaration

I, Catherine Manning, confirm that, apart from where explicitly stated below, all the work presented in this thesis is entirely my own.

David Aagten-Murphy assisted with programming the speed discrimination task described in Chapter 2. The stimuli used in the equivalent noise task (Chapters 4 and 5) were programmed by Marc Tibber and Steven Dakin. Rebecca McMillin, Janina Brede and Anna Rudnicka provided occasional assistance with data collection. I analysed all the data, but used Matlab code provided by Marc Tibber and Steven Dakin for equivalent noise modelling (Chapters 4 and 5).

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List of Publications

The following publications relate to research presented in this thesis:

Chapter 2:

Manning, C., Charman, T., and Pellicano, E. (2013). Processing slow and fast motion in children with autism spectrum conditions. *Autism Research, 6* (6), 531-541.

Chapter 4:

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Chapter 5:

Manning, C., Tibber, M. S., Charman, T., Dakin, S. C., and Pellicano, E. (submitted). Enhanced integration of motion information in children with autism.

Chapter 6:

Manning, C., Charman, T. and Pellicano, E. (submitted). Coherent motion processing in autism: is dot lifetime an important parameter?

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List of abbreviations and acronyms

2D:4D	Ratio between length of second and fourth digit
AD/HD	Attention deficit / hyperactivity disorder
ADOS-G	Autism Diagnostic Observation Schedule-Generic
ADOS-2	Autism Diagnostic Observation Schedule, 2nd edition
(n)AFC	(n-)alternative-forced-choice
AQ	Autism-spectrum Quotient
APA	American Psychiatric Association
BOLD	Blood Oxygen Level Dependent
CA	Chronological age
CDC	Centers for Disease Control and Prevention
CRT	Cathode ray tube
DCD	Developmental Coordination Disorder
DCDQ’07	Developmental Coordination Disorder Questionnaire 2007
deg	Visual degrees
deg/sec	Visual degrees per second
DSM-IV	Diagnostic and Statistical Manual, 4th edition
DSM-5	Diagnostic and Statistical Manual, 5th edition
DTI	Diffusion tensor imaging
EEG	Electroencephalography
EPF	Enhanced Perceptual Functioning
fMRI	Functional magnetic resonance imaging
FSIQ	Full-scale IQ
GSQ	Glasgow Sensory Questionnaire
ICD	International Statistical Classification of Diseases and Related Health Problems
ISI	Interstimulus interval
KMO	Kaiser-Meyer-Olkin measure of sampling adequacy

LCD	Liquid crystal display
LED	Light-emitting diode
LGN	Lateral geniculate nucleus
MEG	Magnetoencephalography
MOT	Multiple object tracking
MST	Medial superior temporal area
MT/V5	Medial temporal area
MTN	Maximum tolerable noise
NICE	National Institute for Health and Care Excellence
PCA	Principal Components Analysis
PDD-NOS	Pervasive Developmental Disorder – Not Otherwise Specified
PIQ	Performance IQ
RGT	Reduced Generalisation Theory
RRB	Repetitive and restricted behaviour
SA	Social affect
SB/RI	Stereotyped behaviour / restricted interests
SIAPA	Structured Interview for Assessing Perceptual Anomalies
SCQ	Social Communication Questionnaire
SEQ	Sensory Experiences Questionnaire
SP	Sensory Profile
SQ	Sensory Questionnaire
SSQ	Sensory Sensitivity Questionnaire
TD	Typically developing
TMS	Transcranial magnetic stimulation
VIF	Variance inflation factor
VIQ	Verbal IQ
WASI	Wechsler Abbreviated Scales of Intelligence
WASI-II	Wechsler Abbreviated Scales of Intelligence, 2nd edition
WCC	Weak Central Coherence

1 General Introduction

This thesis focuses on how children with autism process dynamic visual information, and in particular how they perceive the speeds and directions of moving objects. In the following literature review, I first consider what autism is, before reviewing the evidence for atypical sensation and perception in autism. I then outline what is known about motion processing in typical development, in order to serve as a framework for assessing atypical motion processing in autism. Finally, I draw on the literature review to propose the research questions that I address in the following chapters.

1.1 What Is Autism?

Autism is a developmental condition that is characterised by deficits in social communication and interaction, as well as restricted, repetitive patterns of behaviour or interests (Diagnostic and Statistical Manual of Mental Disorders, DSM-5; American Psychiatric Association [APA], 2013). Deficits in social communication and interaction can include deficits in reciprocity (for example, being less able to take turns in conversation and failing to initiate or respond to typical social interactions), as well as poor use of nonverbal communication (such as eye contact and gestures), and difficulties in understanding and sustaining relationships. Restricted, repetitive patterns of behaviour or interests can include stereotyped movements (such as lining up toys), an insistence on sameness and a desire to adhere to routines, as well as preoccupations with highly specific objects or topics. Unusual sensory responses, which will become the focus of this thesis, are also categorised under restricted and repetitive patterns of behaviour and interests within the DSM-5 (APA, 2013; see Section 1.2). To receive a diagnosis of autism, symptoms must be present within the early years of life (although these may not be apparent until later life), should cause clinically significant impairments in everyday functioning, and should not be better explained by intellectual disability or global developmental delay (DSM-5; APA, 2013). In the absence of established biomarkers, diagnosis relies on behavioural assessments, interviews with the child and family, and reviews of a child's history in relation to the diagnostic criteria (Volkmar et al., 2014). Diagnostic criteria are outlined both in the DSM-5 and in the International Statistical Classification of Diseases and Related Health Problems (ICD-10; World Health Organisation, 1993), which is due to be updated later this year.

Previous conceptualisations of autism have distinguished between autism, Asperger's syndrome and Pervasive Developmental Disorder – Not Otherwise Specified (PDD-NOS; DSM-IV, APA, 2000). Asperger's syndrome refers to individuals who meet the criteria for autism *without* having had a language delay (i.e., using functional language before the age of 3 years), and PDD-NOS refers to those who show some behavioural features of autism but do not meet all criteria (DSM-IV, APA, 2000). However, research has failed to validate these categorisations as separable constructs (e.g., Lord et al., 2012; Witwer & Lecavalier, 2008; see Grzadzinski, Huerta, & Lord, 2013 for review), and as a result, these diagnostic categories have been replaced with a single category – autism spectrum disorder – in the recently published DSM-5 (APA, 2013). Throughout this thesis, the term "autism" will be used to encompass all autism spectrum conditions[1].

It has been proposed by some researchers that autistic traits lie on a continuum across the whole population, with individuals diagnosed with autism at the extreme end of this distribution (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001; Constantino & Todd, 2003). Consequently, some studies measure levels of autistic

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[1] Person-first language will be used interchangeably with the term 'autistic' throughout this thesis to reflect the preferences of some individuals on the autism spectrum (see Brown, 2011; Sinclair, 2013).

traits in the general population using questionnaires such as the autism-spectrum quotient (AQ; Baron-Cohen et al. 2001) and relate these to proposed autism-related behaviours (e.g., A. E. Robertson & Simmons, 2013; Skewes, Jegindø, & Gebauer, 2014). Support for this 'continuum' approach has been provided through genetic studies (Robinson et al., 2011) and correlations between trait measures and diagnostic tools (Constantino et al., 2003). However, some concern has been raised over whether trait measures, such as the AQ, can be used as a reliable proxy for autism (Gregory & Plaisted-Grant, 2013).

1.1.1 Developmental trajectories

There is variability in the age at which a child will meet criteria for a diagnosis of autism (Chawarska, Klin, & Volkmar, 2008), although diagnoses have been shown to be reliable and stable from approximately 24 months (Lord et al., 2006; Stone et al., 1999). However, signs of autism – such as atypical eye gaze and reduced pointing – may emerge much earlier (see Barbaro & Dissanayake, 2009, and E. J. Jones, Gliga, Bedford, Charman, & Johnson, 2014, for review). In a subset of individuals, development might initially proceed in an apparently normal fashion, but be followed by a loss of skills, termed 'regression' (see Barger, Campbell, & McDonough, 2013, for review). Autism is a lifelong condition, although symptoms may change throughout an individual's lifespan (Lord et al., 2006; Volkmar et al., 2014). While it is not possible to 'cure' autism, outcomes can be improved through intervention programmes (Bölte, 2014). Periods of transition (such as that between school and work) can be particularly important for determining changes in phenotypic behaviours and the outcomes faced by autistic individuals (e.g., Schall, Wehman, & McDonough, 2012; Taylor & Seltzer, 2010).

1.1.2 Heterogeneity in symptoms

Autism is a spectrum condition (DSM-5, APA, 2013; Wing, 1986, 1996) encompassing extensive variation in symptom profiles (Mandell, 2011; Volkmar & Klin, 2005). While no longer recognising separate subtypes, the DSM-5 (APA, 2013) attempts to capture some of the heterogeneity in autism through clinical specifiers (such as language ability), and autism severity levels that reflect the amount of support that an individual will require (ranging from Level 1: “requiring support”, to Level 3: “requiring very substantial support”). Peaks in ability are sometimes found in those with autism, with a small proportion of individuals displaying exceptional abilities, or ‘savant’ abilities, such as being able to recall long lists of dates or numbers, or having an exceptional musical talent (Bennett & Heaton, 2012; Howlin, Goode, Hutton, & Rutter, 2009; Mottron et al., 2013).

It has been argued that clinical heterogeneity is a central feature of autism, making the concept of autism as a single, discrete disorder obsolete (Brock, 2014). Accordingly, some researchers have proposed that autism is better conceptualised as a range of overlapping, convergent conditions collectively known as “the autisms” (Geschwind & Levitt, 2007), whereas another more extreme standpoint suggests that autism should be thought of as separable symptoms that should be diagnosed independently (Waterhouse, 2013).

1.1.3 Co-occurrence with other conditions

Autism often occurs alongside other developmental and psychiatric conditions within an individual (see Mannion & Leader, 2013, for review). Simonoff et al. (2008) reported that 70% of individuals with autism in a population-based sample had at least one co-occurring disorder, and 40% had at least two. Within this sample, the most common co-occurring conditions were social anxiety disorder, attention deficit/hyperactivity disorder (AD/HD) and oppositional defiant disorder. Furthermore, approximately 50% of children with autism also have an intellectual disability (Centers for Disease Control and Prevention (CDC), 2012; Charman et al., 2011). Given the frequency of co-occurring difficulties, the National Institute for Health and Care Excellence (NICE, CG128, 2011) has emphasised the importance of considering these conditions when diagnosing and assessing the needs of children with autism.

1.1.4 Brain structure and function

Autism is a neurodevelopmental condition, and for that reason, much research has focused on brain structure and function. I briefly outline the major themes emerging from structural and functional brain research, in turn.

1.1.4.1 Structural differences.

Autistic individuals appear to have larger brain volumes on average compared to typically developing (TD) individuals (Stanfield et al., 2008), although this difference may not persist into adulthood (Amaral, Schumann, & Nordahl, 2008). Increased brain size appears to be due to both increased white matter and grey matter in young children with autism (Courchesne et al., 2001) and increased levels of grey matter may persist into adulthood, unlike levels of white matter (Hyde, Samson, Evans, & Mottron, 2010; see also Amaral et al., 2008, for review). The organisation of white matter in autistic individuals has been shown to be atypical in studies using diffusion tensor imaging (DTI), with reports of both *reduced* white matter integrity (e.g., Keller, Kana, & Just, 2007; Shukla, Keehn, & Müller, 2011) and *increased* white matter integrity in certain regions (e.g., Y. Cheng et al., 2010). Cortical thickness has also been examined, with reports of increased thickness in children (Hardan, Muddasani, Vemulapalli, Keshavan, & Minshew, 2006), and reduced thickness in adults (Hadjikhani, Joseph, Snyder, &

Tager-Flusberg, 2006). Differences in several specific brain regions have also been reported, such as small cell size and increased cell density in the limbic system, fewer Purkinje cells in the cerebellum, and enlargement of the amygdala (see Amaral et al., 2008, and Bauman & Kemper, 2005, for review). It is important to interpret all of these findings within the context of a developing brain, as structural differences evident in early childhood may be absent, or even reversed, by adulthood (Amaral et al., 2008).

1.1.4.2 Functional differences.

Findings of atypical white matter tract integrity have been mirrored by evidence of atypical functional connectivity in autism, for example from studies using functional magnetic resonance imaging (fMRI), electroencephalography (EEG) and magnetoencephalography (MEG). One predominant view is that there is long-range underconnectivity between areas of the cortex and local overconnectivity (Brock, Brown, Boucher, & Rippon, 2002; Courchesne & Pierce, 2005). While research evidence appears to support the concept of long-range underconnectivity, there is little evidence to support the idea of increased local connectivity, which may instead be reduced (Vissers, Cohen, & Geurts, 2012). Just as structural connectivity depends on developmental time course, differences in functional connectivity also change with age (Keehn, Wagner, Tager-Flusberg, & Nelson, 2013). Indeed, while overconnectivity is evident in young children with autism, adolescents and adults with autism appear to have reduced functional connectivity compared to age-matched TD individuals (Uddin, Supekar, & Menon, 2013). It is therefore important that accounts of brain connectivity in autism are placed within a developmental context (Uddin et al., 2013).

1.1.5 Aetiology

Evidence for a strong genetic component in the aetiology of autism has accumulated from twin research (Hallmayer et al., 2011), family recurrence rates (Constantino, Zhang, Frazier, Abbacchi, & Law, 2010) and high-risk infant sibling studies (Ozonoff et al., 2011). In addition to this heritability, spontaneous *de novo* mutations have been shown to play a causal role in the development of autism (see Ronemus, Iossifov, Levy, & Wigler, 2014, for review). Multiple genes have been identified as conferring a genetic 'risk' for developing autism, and these multiple causes may help to understand the heterogeneity found in clinical presentation (Section 1.1.2) (see Jeste & Geschwind, 2014, for review). Environmental influences, such as immune system abnormalities and zinc deficiency, also appear to have a modest influence on the development of autism, and may act as risk factors for autism (see Grabrucker, 2013, for review).

1.1.6 Prevalence of autism

While precise figures vary, it is currently estimated that autism affects 1-2% per cent of the population (Baird et al., 2006; Baron-Cohen et al., 2009; Brugha et al., 2011; CDC, 2014; Elsabbagh et al., 2012; Kim et al., 2011). It has been reported that autism prevalence has increased over recent years (Elsabbagh et al., 2012; Kim et al., 2011). Whereas the CDC estimated the prevalence of autism in the United States to be only 1 in 150 in 2002 (CDC, 2007), this has now increased to 1 in 68 in their most recent estimate from 2010 (CDC, 2014). However, it is difficult to determine how much of this increase reflects a 'real' rise in the number of people being affected by autism, perhaps due to environmental factors, and how much is due to methodological issues (Mandell & Lecavalier, 2014) and changes in diagnostic practices (Charman, 2011; Fombonne, 2005; Gernsbacher, Dawson, & Goldsmith, 2005; Kim et al., 2011; K.

Williams et al., 2005). In a worldwide review of epidemiological studies of autism, Elsabbagh et al. (2012) found no differences in prevalence rates across geographic regions, although few surveys have been conducted in lower income countries.

Autism is more commonly diagnosed in males than females, with a ratio of approximately 4:1 (Baird et al., 2006; Rivet & Matson, 2011), and females are often diagnosed with autism later in their development than males (Begeer et al., 2013). While there may be biological factors that reduce the probability of females developing autism (e.g., Baron-Cohen et al., 2014; Werling & Geschwind, 2013), it has also been suggested that autism has been under-diagnosed in girls (Mandy, Chilvers, et al., 2012), particularly in those who are cognitively able (Hiller, Young, & Weber, 2014). Indeed, it is possible that autistic females present with a subtly different phenotype compared to autistic males, for example, having milder restricted and repetitive behaviours, fewer difficulties at school (Mandy, Chilvers, et al., 2012) and more developed social skills (Head, McGillivray, & Stokes, 2014).

1.2 Sensory processing in autism

In the original characterisations of the condition, Kanner (1943) and Asperger (1944/1991) noted that individuals with autism often have sensory atypicalities. These may include hyper-responsiveness (i.e., heightened responses) and hypo-responsiveness (i.e., attenuated responses) to sensory stimuli and sensory-seeking behaviours for a wide range of sensory modalities (Ben-Sasson et al., 2009; Miller, Anzalone, Lane, Cermak, & Osten, 2007; see also Pellicano, 2013, for review). For example, individuals with autism might be overly sensitive to fluorescent or flickering lights, or might seek out sensory stimulation, for example, by looking intensely at a toy car’s wheels as they spin. In a meta-analysis of sensory symptoms, Ben-Sasson et al. (2009) reported that 45-95%

of those with autism have a higher frequency of sensory behaviours than TD individuals. Furthermore, under- and over-sensitivities to sensory stimuli can co-occur within the same individuals (Baranek, David, Poe, Stone, & Watson, 2006; Ben-Sasson et al., 2009; Lane, Young, Baker, & Angley, 2010). Sensory symptoms are present early in life in autism, from toddlerhood (Ben-Sasson et al., 2007; Rogers, Hepburn, & Wehner, 2003), and have been shown to increase with age (Leekam, Nieto, Libby, Wing, & Gould, 2007; Liss, Saulnier, Fein, & Kinsbourne, 2006; Talay-Ongan & Wood, 2000), at least until 6 to 9 years of age (Ben-Sasson et al., 2009, but see also Kern et al., 2007), and can persist into adulthood (Tavassoli, Miller, Schoen, Nielson, & Baron-Cohen, 2014). Sensory symptoms are found across individuals of all levels of ability (Hilton et al., 2010; Leekam et al., 2007; Rogers et al., 2003), although the extent of these may be dependent on IQ in some domains (Baranek et al., 2013; Leekam et al., 2007; Zachor & Ben-Itzchak, 2014). Sensory sensitivities and sensory-seeking behaviours appear to have a neural basis, with increased or attenuated brain responses to sensory stimuli in those with autism (Donkers et al., 2013; S. A. Green et al., 2013).

Sensory symptoms are related to restricted and repetitive patterns of behaviour in autism (Baranek, Foster, & Berkson, 1997; Boyd, McBee, Holtzclaw, Baranek, & Bodfish, 2009; Boyd et al., 2010; Rogers et al., 2003; Wiggins, Robins, Bakeman, & Adamson, 2009) and this relationship is stronger than that found with the social symptoms of autism (Mandy, Charman, & Skuse, 2012; Rogers et al., 2003). Furthermore, a relationship has been found between sensory sensitivity and levels of autistic traits within the general population (A. E. Robertson & Simmons, 2013). Impaired motor skills have also been widely reported in autism (Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Hilton et al., 2012; see also Bhat, Landa & Galloway, 2011, for review), and it has been suggested that these might be related to atypical sensory processing (Jasmin et al., 2009; T. Liu, 2013), although this relationship may not be causal.

More broadly, sensory symptoms impact many aspects of everyday functioning in those with autism. While sensory experiences can sometimes be enjoyable to those with autism, they can also cause distress (R. Jones, Quigney, & Huws, 2003), and may lead to psychological problems such as anxiety and depression (S. Green, Ben-Sasson, Soto, & Carter, 2012; Pfeiffer, Kinnealey, Reed, & Herzberg, 2005). Heightened sensory sensitivities can also lead to inattention, hyperactivity and oppositional behaviour in the classroom, and consequently, teacher-reported academic underachievement (Ashburner, Ziviani, & Rodger, 2008). Sensory symptoms also predict social functioning (Hilton, Graver, & LaVesser, 2007; Hilton et al., 2010), daily living skills (Jasmin et al., 2009) and maladaptive behaviour (Lane et al., 2010), and can have profound effects on family life (Bagby, Dickie, & Baranek, 2012; Ben-Sasson, Soto, Martinez-Pedraza, & Carter, 2013; Schaaf, Toth-Cohen, Johnson, Outten, & Benevides, 2011).

Understanding atypical sensory functioning in autism is therefore of paramount importance. However, it has been debated whether sensory symptoms constitute a core part of autism (e.g., Gerrard & Rugg, 2009; Wiggins et al., 2009) or whether they are purely secondary, related symptoms (e.g., Rogers & Ozonoff, 2005). Whereas previous diagnostic criteria have considered sensory symptoms as merely associated features of autism (DSM-IV, APA, 2000), the new DSM-5 (APA, 2013) recognises sensory symptoms as a central part of the diagnostic criteria, by including them as a separate criterion within the class of repetitive and restricted patterns of behaviours and interests. Moreover, it has been suggested that sensory differences may give a more direct insight into the primary causes of autism than social cognition deficits alone (Belmonte, 2005; Gerrard & Rugg, 2009; Plaisted, 2001), as sensory differences may lead to the development of other symptoms. For example, atypical sensory input might affect neuronal organisation and the development of language skills which are contingent on consistent visual and auditory inputs (Gerrard & Rugg, 2009).

In summary, the reasons for investigating sensory symptoms in autism are threefold: 1) sensory symptoms are very common; 2) they have a great impact on the lives of individuals with autism and their families, and 3) they may have a developmentally causal role in the development of other symptoms. Despite this importance, the nature of sensory atypicalities and their underlying mechanisms still remain poorly understood (Pellicano, 2013). Much research into sensory atypicalities in autism relies on parent-report measures, such as the Sensory Profile (SP; Dunn, 1999), the Sensory Sensitivity Questionnaire (SSQ; Talay-Ongan & Wood, 2000), the Sensory Questionnaire (SQ; Boyd & Baranek, 2005) and the Sensory Experiences Questionnaire (SEQ; Baranek et al., 2006). Such questionnaires allow potentially low frequency behaviours to be measured across a range of contexts and time frames by a respondent who knows the child well, but they may be biased by an expectation of what symptoms are associated with an autism diagnosis (Rogers et al., 2003).

The sensory experiences of adults can be assessed using self-report questionnaires, such as the Glasgow Sensory Questionnaire (GSQ; A. E. Robertson & Simmons, 2013) and through analysis of first-hand accounts (R. Jones et al., 2003). Noting that the perspectives of children with autism have been overlooked in autism research to date, A. E. Robertson (2012) and Kirby, Dickie, and Baranek (2014) assessed the sensory experiences of children through qualitative interviews. In A. E. Robertson’s study, children with autism aged between 9 and 14 years described both negative and positive sensory experiences, as well as very strong reactions to sensory stimuli. Kirby et al. reported that while some children with autism aged 4 to 13 years thought that their sensory experiences might be exaggerated compared to other people, many children framed their experiences as normal. Children often talked about negative sensory experiences causing a bodily reaction and a sense of being ‘out of control’, and the authors noted that this could lead to fear and anxiety which might limit participation in daily activities. Children reported that their sensory experiences changed over time, which often manifested as reduced aversive experiences. This progression was often reflected on with pride, allowing children to participate more in everyday activities.

Qualitative reports of sensory functioning such as these give insights into the impact of sensory experiences on the everyday lives of individuals with autism and their families. However, it is important to supplement these insights with other methods to characterise more fully the nature of atypical sensory functioning in autism, and the underlying mechanisms. One such approach involves quantifying performance in behavioural tasks using reaction times or sensory thresholds (i.e., measures of how sensitive an individual is to small differences in sensory stimuli) and then comparing these measures between those with and without autism. Vision is one modality that has been investigated extensively in this manner in autism, as I review in the next section.

1.3 Visual processing of static information in autism

As with other sensory modalities, visual sensory symptoms include both hyper- and hypo-sensitivities. Hyper-sensitivities can include an aversion to dark, bright or flickering lights, whereas hypo-sensitivities can include prolonged, intense looking at objects or people and being attracted to lights (Bogdašina, 2003). These reports have been corroborated by a large body of behavioural evidence showing that individuals with autism perceive visual information differently to TD individuals, both for static and dynamic information (see Simmons et al., 2009, for review). While this thesis focuses on how individuals with autism process *dynamic* information, I shall start by briefly summarising the research evidence for atypical processing of *static* information.

Individuals with autism show enhanced performance in visual search tasks (Kaldy, Kraper, Carter, & Blaser, 2011; Kemner, van Ewijk, van Engeland, & Hooge, 2008; O'Riordan & Plaisted, 2001; O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001; Plaisted, O'Riordan, & Baron-Cohen, 1998a), demonstrate superior performance in a block construction task (Shah & Frith, 1993), are quicker at identifying Embedded Figures (Jolliffe & Baron-Cohen, 1997; Shah & Frith, 1983), and show increased discrimination of novel stimuli compared to TD children (Plaisted, O'Riordan, & Baron-Cohen, 1998b). However, individuals with autism do not show enhanced performance for all classes of static stimuli. Given that autism is characterised as a primarily "social" condition, it is unsurprising that individuals with autism have been shown to be less sensitive to face stimuli (e.g., Humphreys, Minshew, Leonard, & Behrmann, 2007; Klin et al., 1999; see Simmons et al., 2009, for review). In contrast, individuals with autism appear to perform comparably to typical individuals in tasks of object perception (e.g., Boucher & Lewis, 1992; Celani, Battacchi, & Arcidiacono, 1999; but see also Behrmann et al., 2006) and shape perception (de Jonge et al., 2007). Although the evidence is mixed, individuals with autism may be less sensitive to colour information (Franklin, Sowden, Burley, Notman, & Alder, 2008; Franklin et al., 2010; Heaton, Ludlow, & Roberson, 2008) and global form information (e.g., Grinter, Maybery, Pellicano, Badcock, & Badcock, 2010; Spencer & O'Brien, 2006; Tsermentseli, O'Brien, & Spencer, 2008).

While research into static visual perception is informative for understanding how individuals with autism perceive the world, the majority of visual information that we process contains dynamic information. Even when objects themselves are static, they frequently move across the retina as a result of eye, head and body movements. It is therefore important to consider how individuals with autism perceive *dynamic* information. First, however, I consider how motion processing develops in TD children, in order to provide a developmental framework for considering how this might be atypical in individuals with autism.

1.4 Motion processing in typical development

Motion processing is an important aspect of visual development as it enables children to track moving objects with their eyes, direct reaches and grasps towards moving objects and navigate within a dynamic world. Motion processing is essential for working out both the direction with which an object moves and also how fast it is moving. Most of what we know about the processing of direction and speed information, however, comes from studies of adult animal and human brains. I briefly review this evidence before considering how these abilities develop through infancy and childhood.

1.4.1 Motion processing in the developed brain

A broad distinction has been made between magnocellular/dorsal and parvocellular/ventral streams of visual processing, which are specialised for processing motion information, and form information, respectively. The magnocellular pathway originates in a class of retinal ganglion cells called parasol cells, which project to magnocellular layers of the lateral geniculate nucleus (LGN) before reaching layers 4Cα and 6 of the primary visual cortex (V1). In parallel, the parvocellular pathway projects from midget ganglion cells to parvocellular layers of the LGN, and then on to layers 4Cβ and 6 of V1 (see Nassi & Callaway, 2009, for review). On reaching the visual cortex, visual information continues to be processed in a parallel fashion. The dorsal stream projects to areas V3a, MT/V5, MST and areas of parietal cortex, while the ventral stream projects to area V4 and areas of the inferior temporal cortex. The dorsal stream has been dubbed the “where” pathway, as it is thought to primarily process information about spatial location, including information about movement from one location to another (Milner & Goodale, 1995; Mishkin, Ungerleider, & Macko, 1983). Conversely, the ventral pathway has been dubbed the “what” pathway, primarily processing information for form, colour and object recognition (Milner & Goodale, 1995; Mishkin et al., 1983).

Within each pathway, processing is broadly hierarchical, with simple features being processed in earlier stages of the visual stream, and more complex stimulus features being processed in higher-order areas. In the dorsal stream, for example, neurons in V1 can signal the presence of *local motion* (i.e., the directions of individual elements; Hubel & Wiesel, 1962), while neurons in MT/V5 play a key role in processing *global motion* (i.e., the overall direction of multiple elements), as they have larger receptive fields capable of integrating inputs from V1 (Mikami, Newsome, & Wurtz, 1986). Cells in MT/V5 respond to both global direction information (Antal et al., 2004; Britten, Shadlen, Newsome, & Movshon, 1992) and speed information (J. Liu & Newsome, 2005; Huk & Heeger, 2000).

Area V3A is also involved in processing motion information (Braddick, O’Brien, Wattam-Bell, Atkinson, & Turner, 2000), playing a particular role in attention to speed information (Sunaert, van Hecke, Marchal, & Orban, 2000). Area MST has even larger receptive fields than MT (Tanaka et al., 1986) and is involved in processing optic flow patterns (systematic changes in the visual array arising from motion) such as rotation, expansion and contraction (Duffy & Wurtz, 1997; Lagae, Maes, Raiguel, Xiao, & Orban, 1994). Areas outside of the dorsal stream pathway have also been associated with motion processing (Braddick et al., 2000; Braddick, O’Brien, Wattam-Bell, Atkinson, & Turner, 2001; Sunaert, van Hecke, Marchal, & Orban, 1999), including a distributed network of cortical areas including V4 (K. Cheng, Hasegawa, Saleem, & Tanaka, 1994; Sunaert et al., 2000), and also the cerebellum (Ivry & Diener, 1991). While the feedforward nature of motion processing is often emphasised, it must be noted that feedback connections also play an important role in such processing, for example in segregating figure-from-ground and disambiguating motion signals (Bayerl & Neumann, 2004; Hupé et al., 1998; Lamme, Super, & Spekreijse, 1998; Sillito, Cudeiro, & Jones, 2006; Raudies & Neumann, 2010).

Adult studies of visual motion processing suggest the existence of at least two distinct systems tuned to different ranges of speed. For example, Burr, Fiorentini, and Morrone (1998) reported different effects of contrast on a motion onset detection task for slow and fast stimuli, M. Edwards, Badcock, and Smith (1998) reported speed-specific effects of noise on coherent motion perception, and Fesi, Thomas and Gilmore (2014) showed pattern-specific processing of optic flow information for slow but not fast speeds. Accordingly, models of motion processing have proposed distinct channels for processing slow and fast motion (e.g. Thompson, Brooks, & Hammett, 2006, see review by Burr & Thompson, 2011). It has been suggested that these channels may correspond to parvocellular/ventral and magnocellular/dorsal channels (Gegenfurtner & Hawken, 1996; Hammett, Champion, Morland, & Thompson, 2005; Lorteije, Van Wezel, & Van der Smagt, 2008; Perrone, 2005; reviewed by Burr & Thompson, 2011).

While both speed and direction are processed in MT/V5, it is not clear whether they are processed in a similar fashion. Many models of speed processing assume that they are processed via similar mechanisms (e.g., Ascher & Grzywacz, 2000; Perrone & Thiele, 2002), and accordingly, Van der Smagt, Verstraten, and Paffen (2010) reported that centre-surround interactions have a similar effect on perceived speed as on direction discrimination. However, there is also evidence to suggest that direction and speed are processed differently. For example, transcranial magnetic stimulation (TMS) has different effects on perceived direction and speed (Matthews, Luber, Qian, & Lisanby, 2001), and direction and speed appear to be represented differently in MT, with direction selectivity but not speed selectivity being organised in a columnar fashion (J. Liu & Newsome, 2003).

1.4.2 The development of direction processing

Given the importance of motion processing in visual development, it is perhaps unsurprising that some aspects of direction processing develop early, in the first few months of life (see Braddick & Atkinson, 2011, for review). The ability to process local direction information emerges before the ability to process global direction information (Hou, Gilmore, Pettet, & Norcia, 2009). For instance, direction selectivity emerges at around 10 to 12 weeks of age, with direction selectivity for stimuli moving at 5 deg/sec emerging earlier than that to a faster speed of 20 deg/sec (Wattam-Bell, 1991). Within the next few months of life, infants are sensitive to coherent motion displays, whereby a proportion of randomly positioned dots move in a coherent direction amongst randomly moving noise dots (Blumenthal, Bosworth, & Dobkins, 2013), and infants can use this coherent motion information to extract depth information (Hirshkowitz & Wilcox, 2013). Infants are also able to perceive a human form in a moving point-light display, in “biological motion” tasks (Booth, Pinto, & Bertenthal, 2002; R. Fox & McDaniel, 1982), and are sensitive to optic flow information (Gilmore, Hou, Pettet, & Norcia, 2007). Motion-sensitive areas such as MT/V5 appear to be almost adult-like from 7 weeks (Morrone, 2014), which may underlie these early motion-processing abilities.

Although sensitivity to direction information onsets in the first year of life, some aspects of direction processing continue to develop long into childhood. For example, the minimum speed required to support perception of motion-defined form and the maximum displacement supporting perception of movement mature by around 7 to 8 years (Hayward, Truong, Partanen, & Giaschi, 2011; Parrish, Giaschi, Boden, & Dougherty, 2005), motion coherence thresholds reach adult-like levels between 10 and 14 years (Gunn et al., 2002; Hadad, Maurer, & Lewis, 2011) and biological motion thresholds improve steadily up until 14 years (Hadad, Maurer, & Lewis, 2011). This gradual development may be due to developments in the integrative properties of high-level motion areas (Movshon, Rust, Kohn, Kiorpes, & Hawken, 2004) and/or changes in subcortical input and connectivity between cortical areas (Morrone, 2014).

There is some evidence to suggest that the distinct speed-tuned systems proposed in adults (Section 1.4.1) follow different rates of development. Hayward et al. (2011) reported that sensitivity to motion-defined form developed more gradually for the slowest speed tested (0.1 deg/sec) compared to faster speeds of 0.9 and 5 deg/sec, and Narasimhan and Giaschi (2012) found that children aged 5 to 6 years had more immature motion coherence thresholds for slow (1 deg/sec) stimuli compared to fast (4 deg/sec) stimuli. Hadad et al. (2011) did not find different developmental rates in their two speed conditions (4 deg/sec and 18 deg/sec), but this may be because both of these speeds fall within the range of a single speed-tuned system.

Recent research has considered the reasons for differences in sensitivity to slow and fast speeds in development. Bogfjellmo, Bex, and Falkenberg (2014) have suggested that reduced sensitivity to direction information at slow speeds is due to both differences in the precision with which local directions are coded, and the ability to average over multiple stimulus elements. Meier and Giaschi (2014) have suggested that differences in sensitivity are due to the precise spatial and temporal offsets in the stimuli, rather than necessarily speed per se.

1.4.3 The development of speed processing

As well as being sensitive to direction information within the first few months of life, infants are also sensitive to speed information. Infants have been shown to use speed information for guiding eye tracking movements (Mareschal, Harris, & Plunkett, 1997) and individuating objects (Wilcox, Hawkins, Hirskkowitz, & Boas, 2014; Wilcox & Schweinle, 2003). The ability to discriminate between two different speeds improves with age (Aslin & Shea, 1990; Möhring, Libertus, & Bertin, 2012), and young infants appear to be more sensitive to fast speeds than slow speeds. For example, Volkmann and Dobson (1976) showed that fixation preferences for a dynamic checkerboard over a stationary checkerboard were stronger for rapid rates of movement than slower rates of movement in 1- to 3-month-old infants. In a similar preferential looking experiment, Aslin and Shea (1990) investigated the speed discrimination thresholds of 6- and 12-week-old infants, by presenting them with sets of moving stripes. At 6 weeks, infants could not discriminate stationary targets from targets moving slower than 9 deg/sec, and at 12 weeks, infants could not discriminate stationary targets from those moving under 4 deg/sec. It seems that, in the first few months of life, sensitivity to slow moving stimuli is more immature than sensitivity to faster moving stimuli, but that there is a reasonably rapid development of sensitivity.

Just as in direction processing, this initial period of rapid development is followed by a long, protracted rate of development through childhood, reaching adult-like levels only by mid-to-late childhood (C. Manning, Aagten-Murphy, & Pellicano, 2012). In line with infant research, sensitivity to slow speeds appears to develop more gradually than that to fast speeds (Ahmed, Lewis, Ellemberg, & Maurer, 2005; C. Manning et al., 2012). Whereas sensitivity to a fast reference speed (6 deg/sec) reaches adult-like levels by 11 years of age, sensitivity to a slow reference speed (1.5 deg/sec) matures at some point after 11 years (C. Manning et al., 2012).

To summarise, the development of sensitivity to both direction and speed information begins in the first few months of life, but long, protracted rates of development are seen for many aspects of motion processing, such as motion coherence and speed discrimination. It has been suggested that such motion processing abilities might be limited in childhood by poor integration of local motion cues over space (e.g., Ahmed et al., 2005; Bogfjellmo et al., 2014; Hadad et al., 2011; C. Manning et al., 2012). Some research suggests that sensitivity to slow speeds may develop more gradually compared to faster speeds. The long, gradual development of motion processing abilities, particularly for slow speeds, may make motion processing susceptible to atypical developmental trajectories, for example in autism. I now review the evidence that individuals with autism perceive motion information differently to typical individuals.

1.5 Visual processing of dynamic information in autism

Individuals with autism show comparable sensitivities to TD individuals for flicker contrast (Bertone, Mottron, Jelenic, & Faubert, 2005; R. A. O. Davis, Bockbrader, Murphy, Hetrick, & O'Donnell, 2006; Pellicano, Gibson, Maybery, Durkin, & Badcock, 2005) and for contrast in first-order (i.e., luminance-defined) moving stimuli (Bertone, Mottron, Jelenic, & Faubert, 2003). A recent unexpected finding showed that individuals with autism display *enhanced* performance in a basic motion task, requiring shorter stimulus durations than typical individuals to accurately report the direction of briefly presented gratings (Foss-Feig, Tadin, Schauder, & Cascio, 2013).

However, *reduced* sensitivity has been reported for more complex motion tasks. Some of the earliest evidence for this came from studies showing decreased postural reactivity in response to optic flow patterns (Gepner & Mestre, 2002; Gepner, Mestre, Masson, & de Schonen, 1995; Price, Shiffrar, & Kerns, 2012). However, such studies do not provide conclusive evidence for motion processing atypicalities, as they may be confounded by atypical postural control and proprioceptive feedback mechanisms. Indeed, there is evidence that individuals with autism show altered postural stability even in the absence of visual motion information (Molloy, Dietrich, & Bhattacharya, 2003). Subsequent studies have demonstrated atypical motion processing abilities whilst eliminating motor demands, as reviewed in the following sections.

1.5.1 Biological motion perception

Blake, Turner, Smoski, Pozdol, and Stone (2003) reported that individuals with autism are less sensitive to biological motion information than typical individuals. This finding has since been replicated (Annaz et al., 2010; Koldewyn, Whitney, & Rivera, 2010, 2011; McKay, Mackie, Piggott, Simmons, & Pollick, 2006; Nackaerts et al., 2012; Price et al., 2012) and it has been shown that young children with autism do not preferentially attend to biological motion, whereas TD children do (Annaz et al., 2012; Klin, Lin, Gorrindo, Ramsay, & Jones, 2009). Additionally, toddlers with autism are not cued to a target by pointing within a biological motion display unlike TD children (Swettenham et al., 2013). However, other researchers have failed to find evidence of impaired biological motion perception in autism (C. R. G. Jones et al., 2011; Murphy, Brady, Fitzgerald, & Troje, 2009; Rutherford & Troje, 2012; Saygin, Cook, & Blakemore, 2010). While a range of stimulus, task and participant differences are likely to contribute to these discrepant findings (M. Kaiser & Shiffrar, 2009), an emergent theme is that individuals with autism may have particularly pronounced difficulties when they are required to discriminate the emotion of a biological motion stimulus (A. Atkinson, 2009; Hubert et al., 2007; Moore, Hobson, & Lee, 1997; Parron et al., 2008).

Importantly, even when behavioural performance is indistinguishable between individuals with autism and TD individuals, the neural underpinnings may differ. In an fMRI study of biological motion perception, Herrington et al. (2007) reported that individuals with Asperger's syndrome had less activity than typical individuals in several brain regions including the motion-processing area, MT/V5. In contrast, Koldewyn, Whitney, and Rivera (2011) reported similar levels of activity in MT/V5, but reduced activity in higher-order social and attentional areas in those with autism, such as in the posterior superior temporal sulcus, and parietal and frontal regions. Freitag et al. (2008) and McKay et al. (2012) showed that people with autism employ different networks of brain regions compared to typical individuals when processing biological motion information. In line with this, Kröger et al. (2014) reported atypicalities in both early sensory processing and in top-down processing using EEG.

As suggested by McKay et al. (2012), individuals with autism may develop compensatory strategies for performing biological motion tasks as they get older. This suggestion is particularly conceivable given that studies comparing adolescents or adults with and without autism often show no differences in sensitivity (e.g., C. R. G. Jones et al., 2011; Saygin et al., 2010) whereas studies investigating young children do show atypicalities (Annaz et al., 2012; Klin et al., 2009). Individuals with higher levels of intellectual functioning may be better equipped to develop compensatory strategies, which may explain the link between biological motion thresholds and IQ reported by C. R. G. Jones et al. (2011) and Rutherford and Troje (2012). Biological motion tasks have been classified as a type of 'social perception' (Zilbovicius et al., 2006; see also Pavlova, 2012), and so it is possible that individuals with autism might have particular difficulties in these tasks due to a reduced interest in social stimuli (Chevallier, Kohls, Troiani, Brodkin, & Schultz, 2012; Dawson, Meltzoff, Osterling, Rinaldo, & Brown, 1998). Other studies, however, have demonstrated that individuals with autism also have difficulties in processing motion for non-social stimuli, for example when detecting the overall, global direction of a random dot pattern, as reviewed in the next section.

1.5.2 Global direction processing

Motion coherence tasks (Newsome & Paré, 1988, see Section 1.4.2) have been extensively used to assess the motion-processing abilities of individuals with autism (see Table 1.1). In these tasks, observers are typically asked to report the direction of coherently moving dots amidst randomly moving noise dots, and a threshold is taken as the minimum proportion of coherently moving (signal) dots required for accurate discrimination. As these tasks cannot be performed by processing single dots alone, motion coherence thresholds are assumed to reflect global motion processing. Indeed, motion coherence tasks activate areas of the brain involved in integrating motion signals, such as area MT/V5 (Britten et al., 1992, Tootell et al., 1995).

Table 1.1 Summary of psychophysical studies investigating motion coherence sensitivity in individuals with autism

Study	*Stimuli*	*Monitor type*	*Task*	*Dot speed (deg/sec)*	*Stimulus duration (ms)*	*Dot lifetime (ms)*	*Dot diameter (deg)*	*Dot density (dots/deg^2)*	*Participants with autism*	*Comparison participants**	*Results (%)*
Spencer et al. (2000)	2000 white dots on grey background; 30 x 22 deg; 2 panels, one with a strip of coherently moving dots oscillating in opposite phase to those in surrounding region; Horizontal translation, reversing direction every 330ms	LCD	2AFC motion coherence detection: locate target strip	5.8	Self-limited	17[a]	Not specified	4	7-11yrs, n=23	n=50, matched on verbal MA	Autism: higher thresholds
Milne et al. (2002)	150 white dots on black background; Horizontal translation in proportion of dots	LCD	2AFC direction discrimination with feedback	8.8	1010	224	1 pixel	0.3	9-15yrs, n=25	9-15yrs, n=22, matched on CA & PIQ	Autism: higher thresholds
Pellicano et al. (2005)	100 white dots on black background; 18 x 14 deg; Vertical translation in proportion of dots	CRT	2AFC direction discrimination with feedback	6.3	600	30[b]	0.1	0.4	8-12yrs, n=20	8-12yrs, n=20, matched on CA & nonverbal ability	Autism: higher thresholds
R. A. O. Davis et al. (2006)	100 black dots on grey background; 6.3 x 6.3 deg; Horizontal translation in proportion of dots	CRT	2AFC direction discrimination	6.4	220, 1000	Not specified	0.1	2.52[d]	10-18yrs, n=9	7-15yrs, n=9, matched in CA & verbal ability	Autism: higher thresholds only for 1000ms duration
Del Viva et al. (2006)	100 black and white dots on grey background; 15 x 15 deg; 3 conditions specifying movement of coherent motion: translation, circular and radial motion	LCD	2AFC direction discrimination	10	160	66	0.1	0.44[d]	6-14yrs, n=10	Group 1: 6-7yrs, n=12, matched on MA; Group 2: 8-12yrs, n=14, matched on CA	Autism: no difference in thresholds compared to either comparison group
Milne et al. (2006)	600 white dots on black background; 2 panels (each 10 x 14 deg), one with proportion of coherent motion; Horizontal translation; Direction reversed every 572ms	Not specified	2AFC coherence detection: Which panel has coherent motion?	7	2300	85	0.1	2.1	8-12yrs, n=23	8-12yrs, n=23, matched on CA & non-verbal ability	No overall group difference. Subgroup (22%) of autism group had elevated thresholds

Study	*Stimuli*	*Monitor type*	*Task*	*Dot speed (deg/sec)*	*Stimulus duration (ms)*	*Dot lifetime (ms)*	*Dot diameter (deg)*	*Dot density (dots/deg^2)*	*Participants with autism*	*Comparison participants**	*Results (%)*
Spencer & O'Brien (2006)	Glass patterns of white dots on black background; Circle of coherent circular motion (radius 6.6 deg) on left or right of screen.	LCD	2AFC motion coherence detection: Locate target circle	5.8	250	50	Not specified	4	Autism: M= 13.5yrs (SD=3.3), n=15; Aspergers: M= 12.0yrs (SD=3.6), n=10	M=11.7yrs (SD=2.4), n=15, matched on CA & verbal MA	Autism: higher thresholds; Aspergers: no group difference compared to comparison group
de Jonge et al. (2007)	White dots on black background; 3 vertically aligned panels (each 5.7 x 5.7 deg); Horizontal translation.	CRT	2AFC oddity paradigm: is bottom or top stimulus the "odd one out"?	Not specified	Self-limited	Not specified	1 pixel	Not specified	7-33yrs, n=29	7-33yrs, n=32, matched on CA, VIQ & PIQ	No group difference
Pellicano & Gibson (2008)[c]	100 white dots on black background; 18 x 14 deg; Vertical translation in proportion of dots.	CRT	2AFC direction discrimination with feedback	6.3	600	30[b]	0.11	0.4	8-12yrs, n=20	TD: 8-12yrs, n=61, matched on CA & PIQ; Dyslexia: 8-12yrs, n=41, matched on CA, PIQ & VIQ	Autism: higher thresholds than TD group and similar thresholds as dyslexia group
Takarae et al. (2008)	100 white dots on black background within 2 circular apertures (7.5 deg diameter); One aperture contains coherent horizontal translational motion in proportion of dots.	CRT	2AFC coherence detection: Which aperture contains coherent motion?	3.3	300	100	0.15	2.26[d]	Autism + language delay: M=16.3yrs (SD=7.2); n=37; Autism without language delay: M=15.3 (SD=5.4), n=27	M=16.5yrs (SD=6.0); n=46 Matched on CA & FSIQ	Autism + language delay: elevated threshold; Autism without language delay: no group difference
Tsermentseli et al. (2008)	Glass pattern of white dots on black background; Circle of coherent circular motion (radius 6.6 deg) on left or right of screen.	Not specified	2AFC motion coherence detection: Locate target circle	5.8	250	50	Not specified	4	17-40yrs, n=21	TD: 17-40yrs, n=20, matched on CA & FSIQ; Dyslexia: 17-40yrs, n=20, matched on CA & FSIQ	No overall group difference. Autism: higher thresholds than TD and dyslexia groups; Aspergers: no difference

Study	*Stimuli*	*Monitor type*	*Task*	*Dot speed (deg/sec)*	*Stimulus duration (ms)*	*Dot lifetime (ms)*	*Dot diameter (deg)*	*Dot density (dots/deg^2)*	*Participants with autism*	*Comparison participants**	*Results (%)*
A. Atkinson (2009)	750 white dots on black background; 17.1 x 7.4 deg[d]; Horizontal translation in proportion of dots	Not specified	2AFC direction discrimination	~ 0.2[d]	200	Not specified	~1mm	~5.9[d]	18-58yrs, n=13	17-5yrs, n=16, matched on CA, VIQ & PIQ	Autism: higher thresholds at borderline significance, *p*=.054
Annaz et al. (2010)	White dots on black background; 2 panels, one with translational motion (direction not specified) in a proportion of dots	LCD	Coherence detection: Which panel has coherent motion?	3.2	Not specified	Not specified[e]	Not specified	Not specified	5-12yrs, n=23.	4-12yrs, n=34, matched on CA & nonverbal ability	Autism: higher thresholds
Koldewyn et al. (2010)	Black dots on white background; 10.7 x 8.5 deg. Varied distribution of dot directions from 0 (coherent) to 360 (incoherent) deg. Mean motion horizontal translation	Not specified	2AFC direction discrimination	Variable: 4.5 – 9	2000	Not specified	Not specified	Not specified	11-19yrs, n=30	11-19yrs, n=32, matched on CA	Autism: higher thresholds, but group difference disappeared when IQ added as covariate
C. R. G. Jones et al. (2011)	White dots on black background. 2 panels (13.7 x 13.7 deg), one with horizontal translational motion in a proportion of dots	LCD	Coherent motion detection: Which panel has coherent motion?	2.5	Self-limited (up to 6000ms)	40	0.23	Not specified	14-16yrs, n=89	Non-autism: 14-16yrs, n=52, matched on CA, VIQ & PIQ, includes TD (n=28) & those with other diagnoses (n=24)	No group difference
Chen et al. (2012)	200 white dots on black background within circular aperture (7 deg diameter). Horizontal translation	Not specified	2AFC direction discrimination	5.25	300	Unlimited	0.03	5.20[d]	13-18yrs, n=19	13-18yrs, n=17, matched on CA	No group difference
Price et al. (2012)	600 white dots on black background; 2 (10x14 deg); one panel with proportion of coherent motion; Horizontal translation; Direction reverses every 572ms	Not specified	Coherence detection: Which panel has coherent motion?	7[f]	2300[e]	200	0.1[f]	2.1[f]	7-23yrs, n=14	7-23yrs, n=16, matched on CA, verbal and non-verbal ability	No group difference

Study	*Stimuli*	*Monitor type*	*Task*	*Dot speed (deg/sec)*	*Stimulus duration (ms)*	*Dot lifetime (ms)*	*Dot diameter (deg)*	*Dot density (dots/deg^2)*	*Participants with autism*	*Comparison participants**	*Results (%)*
C. E. Robertson et al. (2012)	150 white dots; Circular aperture diameter 9 deg	LED	2AFC direction discrimination	5	200, 400, 1500	~50[g]	0.04	1.85	M=24.7yrs (SD=3.5), n=20	M=30.3yrs (SD=11.7), n=20, matched on CA[h]	Autism: higher thresholds only at shortest duration
Ronconi et al. (2012)	White dots on black background; Central condition: circular aperture diameter 7.5 deg; Peripheral condition: annulus composed of outer circle 21deg and inner circle 16 deg diameter; Horizontal or vertical translation	CRT	4AFC direction discrimination	12	300	~50	0.05, 0.15	17	9-18yrs, n=11	11-18yrs, n=11, matched on CA and non-verbal ability	Autism: higher thresholds only in central condition
Koldewyn et al. (2013)	100 white dots on black background; 12.5 x 12.5 deg aperture	Not specified	2AFC direction discrimination	11	1000	50	0.2	0.64[d]	5-12yrs, n=28.	5-12yrs, n=26, subset of larger group who were matched on CA & PIQ	No group difference
C. E. Robertson et al. (2014)	150 white dots; Circular aperture diameter 9 deg	LCD	2AFC direction discrimination	5	200, 600	~50[g]	0.04	1.85	16-27yrs, n=18	15-23yrs, n=18, matched on CA, VIQ & PIQ	Autism: higher thresholds at shortest duration

Note. yrs = years; 2AFC = 2-alternative-forced choice; 4AFC = 4-alternative-forced-choice; CA = chronological age; MA = mental age; FSIQ = full-scale IQ; PIQ = performance IQ; VIQ = verbal IQ. * Typically developing (TD) unless stated otherwise. [a] Noise dots randomly replotted on each frame. [b] The identity of dots (signal or noise) was randomly chosen every 30 ms. [c] Reanalysis of data from Pellicano et al. (2005) and Gibson et al. (2006). [d] Information not explicitly stated – calculated from information provided. [e] Authors report that lifetime was 1 frame, but frame duration not specified. [f] Not explicitly stated, but authors report that they use the same procedure as Hansen et al. (2001). [g] One third of dots replaced every 16.6ms. [h] Nonverbal IQ data not available for all participants, but no significant group differences in subset tested.

Spencer et al. (2000) found that children with autism had elevated motion coherence thresholds compared to TD children, despite having equivalent thresholds in a form coherence task. Many other studies have similarly shown that individuals with autism have significantly higher motion coherence thresholds than TD individuals (Annaz et al., 2010; Koldewyn et al., 2010; Milne et al., 2002; Pellicano et al., 2005). This finding has been extended to tasks that require the location of shapes formed by coherent motion (Annaz et al., 2010; Spencer & O'Brien, 2006), which Annaz et al. (2010) term 'form-from-motion'. Furthermore, members of the general population with high levels of autistic traits have higher motion coherence thresholds than those with low levels of autistic traits (Grinter et al., 2009). However, other studies have failed to find evidence of elevated motion coherence thresholds in autism, instead finding comparable thresholds between individuals with autism and TD individuals (de Jonge et al., 2007; Del Viva, Igliozzi, Tancredi, & Brizzolara, 2006; C. R. G. Jones et al., 2011; Koldewyn, Weigelt, Kanwisher, & Jiang, 2013; Milne et al., 2006; Price et al., 2012). Vandenbroucke, Scholte, Engeland, Lamme, and Kemner (2008) also reported no difficulties in global motion processing in a different task, whereby participants were presented with two superimposed moving plaids and were asked to report if they were seen to move coherently, or as two transparent components. In this task, autistic adults reported perceiving coherent motion to the same extent as typical adults.

These discrepant results may be attributed, at least in part, to differences in participant characteristics. Comparisons are often made at the group level, but there is a substantial amount of individual variability, with approximately only 22-40% of individuals with autism showing elevated motion coherence thresholds (Milne et al., 2002, 2006; Pellicano & Gibson, 2008). Furthermore, Takarae, Luna, Minshew, and Sweeney (2008) found elevated motion coherence thresholds only in individuals with autism who also had delayed language, and not those without a language delay. As only a subset of individuals with autism display elevated motion coherence thresholds, it is therefore possible that sampling differences contribute to discrepant findings, especially when small sample sizes are used. As with biological motion, a relationship has been established between both verbal and non-verbal IQ and coherent motion sensitivity in autism (Koldewyn et al., 2010). It is therefore important to consider this when matching groups of individuals with and without autism and when interpreting the results of existing studies. While most studies match their groups in terms of non-verbal or full-scale IQ, groups of individuals with autism often have lower levels of verbal IQ (e.g., Annaz et al., 2010; Milne et al., 2002; Pellicano et al., 2005). In practice, it can be difficult to match groups on both verbal and nonverbal ability, as individuals with autism tend to have different IQ profiles, with poorer verbal ability relative to their nonverbal ability (Jarrold & Brock, 2004).

A further reason for discrepant findings in motion coherence tasks relates to task and stimulus parameters. Indeed, C. E. Robertson, Martin, Baker, and Baron-Cohen (2012) showed that autistic adults had elevated motion coherence thresholds only when the stimuli were presented for a short duration of 200 ms, and not when presented for longer durations of 400 ms or 1500 ms. R. A. O. Davis et al. (2006) reported precisely the opposite effect, with individuals with autism showing elevated thresholds for a long stimulus (1000 ms) and not a short stimulus (200 ms). However, R. A. O. Davis et al.'s result may have been spurious as it was based on a small sample of individuals with autism ($n = 9$) and TD individuals ($n = 9$). C. E. Robertson and colleagues later replicated their original finding showing elevated thresholds at a short stimulus duration (200 ms versus 600 ms) in autistic adults compared to TD individuals (C. E. Robertson et al., 2014). C. E. Robertson et al. (2012) therefore suggested that individuals with autism atypically integrate motion signals over time, which may be masked by longer viewing durations. Similarly, Ronconi et al. (2012) found elevated motion coherence thresholds in children with autism only when stimuli were viewed centrally, and not peripherally. As shown in Table 1.1, studies of coherent motion sensitivity in autism have used a wide variety of different stimulus parameters, making it difficult to compare across studies. It is therefore important to investigate the effects of different stimulus parameters within the same individuals, whilst controlling all other variables.

Echoing studies of biological motion perception, the neural mechanisms underlying coherent motion perception in individuals with autism and TD individuals appear to differ. fMRI studies reveal atypical activation patterns in individuals with autism in response to coherent motion, both at lower and higher levels of the motion-processing pathway (Brieber et al., 2010; C. E. Robertson et al., 2014; Takarae, Luna, Minshew, & Sweeney, 2014). While these fMRI studies show that the neural correlates underlying coherent motion processing in autism are atypical, EEG and MEG offer the potential to pinpoint the temporal scale of atypical neural processing in autism. For example, Greimel et al. (2013) showed that adolescents with autism show a reduced N200 component, but a typical P400 component, and suggested that this reflected general difficulties with motion processing, rather than abnormal integration of information. It is therefore clear that the neural underpinnings of coherent motion perception are atypical in autism and it remains a challenge for future work to link these findings to the discrepant results found at the behavioural level.

1.5.3 Multiple object tracking

In the multiple object tracking (MOT) paradigm, participants are required to track target objects moving in different directions amongst distracters. Koldewyn, Weigelt, Kanwisher, and Jiang (2013) showed that children with autism aged 5 to 12 years were able to track fewer objects than TD children across a range of object speeds between 6.4 and 28.8 deg/sec. Koldewyn et al. argued that atypical dynamic attention would lead to particularly pronounced difficulties at fast speeds and hence concluded that children with autism had similar dynamic attentional function as TD children. They also showed that MOT capacity was unrelated to sensitivity to coherent motion, arguing that differences in basic motion processing ability do not explain MOT performance in autism. However, motion coherence tasks are thought to require integration across multiple stimulus elements, whereas the MOT task requires separate, distinct representations of the targets. Therefore, it is still possible that MOT performance may be limited by other aspects of basic motion processing in autism. Furthermore, static comparison tasks are necessary to determine whether a reduced ability to maintain representations of individual objects is specific to dynamic stimuli.

O'Hearn, Franconeri, Wright, Minshew, and Luna (2013) used a MOT task alongside a static rapid enumeration task to measure individuation ability (i.e., the ability to perceive a small number of elements simultaneously), whilst investigating how grouping facilitates or hinders performance. As reported by Koldewyn et al. (2013), individuals with autism were able to track fewer items than typical individuals in the MOT task. Interestingly, they also showed that individuals could rapidly count fewer static elements, suggesting that reduced individuation capability is not specific to dynamic tasks. For both participants with autism and typical individuals, MOT performance improved when target-target pairs were grouped with distracter-distracter pairs, whereas performance was hindered when targets were paired with distracters. This suggests that grouping information is processed similarly in individuals with autism as in TD individuals. In contrast, however, Evers et al. (2014) reported a *weaker* detrimental effect of grouping targets to distracters in children with autism. While research into MOT ability in autism is still in its early stages, it appears that MOT performance differs in individuals with autism compared to typical individuals. The exact nature of this atypical performance requires further clarification.

1.5.4 Speed processing

Much research has investigated the processing of direction information in autism, but little research has focused on how individuals with autism process speed information. Yet, there is both anecdotal and empirical evidence to suggest that individuals with autism might process speed-related information atypically. Autobiographical reports suggest that the world "moves too fast" for at least some individuals with autism (Grandin, 1995; D. Williams, 1999). Empirically, it has been shown that children with autism can recognise facial expressions better when video stimuli are slowed down (Gepner, Deruelle, & Grynfeltt, 2001) and individuals with autism show weaker oculomotor reactivity specifically for fast stimuli (Mestre et al., 2002). Furthermore, children with autism aged 12 to 15 years, but not older adolescents, show altered postural stability in response to a virtual environment moving specifically at high oscillation frequencies (Greffou et al., 2012). However, the benefit of slowing down stimuli may not point to problems processing fast-moving stimuli *per se*: it may be that slowing stimuli down increases the salience of important cues for individuals with autism.

In the first study investigating sensitivity to speed differences in autism, Chen et al. (2012) asked autistic adolescents and TD adolescents aged between 13 and 18 years to report which of two successively presented random dot patterns moved faster. In one condition, the stimuli were separated by a short interstimulus interval (ISI) of 500 ms, and in another condition, they were separated by a longer ISI of 3000 ms. Interestingly, the autistic individuals had comparable thresholds to the TD individuals when the ISI was short, but *lower* thresholds (i.e., increased sensitivity) compared to the TD individuals when the ISI was prolonged to 3000 ms. Chen et al. interpreted this pattern of findings as evidence of *enhanced* local processing of dynamic information in autism which is only manifest at longer ISIs due to the requirement for a prolonged temporal window for visual processing in individuals with autism. Future research is needed to replicate this finding and to investigate further the effect of different stimulus parameters, like ISI length, on the speed discrimination thresholds of individuals with autism.

1.5.5 Summary of motion processing abilities in autism

Much research has focused on how individuals with autism process motion information, with particular emphasis given to how individuals with autism process biological and coherent motion information. Not all studies report difficulties in motion processing, and indeed, some report areas of enhanced motion processing ability (Chen et al., 2012; Foss-Feig et al., 2013). Discrepant results are likely to be due, at least in part, to differences in participant characteristics and task and stimulus parameters. However, a general theme is that motion processing difficulties arise for more complex tasks, such as those involving integration of motion information over space, or those involving a social or motor control component. This raises an important question as to the extent that atypical performance in motion processing tasks results from basic sensory differences, or from atypical top-down influences. Even when behavioural performance is indistinguishable, it appears that the neural underpinnings of motion processing are different for individuals with autism and TD individuals. Such differences at the neural level may be compensated for through development.

Having reviewed the evidence for atypical motion processing in individuals with autism, I shall now consider a range of explanations that have been proposed to account for these data. Note that this is not intended to be a complete list of theories of autism, but a selection of accounts that have tried to account for, or make specific predictions about, atypical motion perception in autism.

1.6 Theories of atypical motion processing in autism

1.6.1 Dorsal/magnocellular accounts

Braddick and colleagues have argued that dorsal and ventral stream functions (see Section 1.4.1) progress along different trajectories in the developing brain, with dorsal stream functions onsetting later and following a more extended development than ventral stream functions (Braddick, Atkinson & Wattam-Bell, 2003). Moreover, it has been suggested that the dorsal stream is particularly vulnerable to developmental insult (J. Atkinson et al., 1997; Braddick et al., 2003; Spencer et al., 2000). Dorsal stream functions such as motion processing would therefore be expected to be disproportionately impaired in a range of developmental conditions, including autism. Support for this 'dorsal stream hypothesis' comes from evidence of motion processing impairments and typical form processing in a range of developmental conditions such as dyslexia (e.g., Demb, Boynton, Best, & Heeger, 1998; Hansen, Stein, Orde, Winter, & Talcott, 2001), Fragile X syndrome (Kogan et al., 2004) and Williams Syndrome (J. Atkinson et al., 1997, 2006; but see also Palomares & Shannon, 2013) [see Grinter, Maybery, & Badcock, 2010, for review].

To determine whether the dorsal stream hypothesis can specifically account for motion processing difficulties in autism, it is important to compare performance in an equivalent, static task. Initial attempts to do this were unsuccessful. Spencer et al. (2000) reported that individuals with autism had elevated motion coherence thresholds, but typical form coherence thresholds, in support of the dorsal stream hypothesis. However, these two tasks were not equivalent, as participants were required to detect a 'ball' of aligned elements amongst a background of randomly oriented line elements in the form coherence task, and a band of coherently moving dots in the motion coherence task. Furthermore, Milne et al. (2002) did not present a comparison form task at all, leaving it unclear as to whether elevated thresholds were specific to the dorsal stream. Indeed, when Spencer and O'Brien (2006) and Tsermentseli et al. (2008) used comparable form and motion coherence tasks, they found that individuals with autism had elevated thresholds in both tasks. Also, evidence from other paradigms has suggested that atypical visual processing is not confined to the dorsal stream in autism (see Section 1.3, and Grinter et al., 2010, for review). However, Greenaway, Davis and Plaisted-Grant (2013) have provided clear evidence of a specific deficit in the magnocellular pathway in autism, showing that children with autism have elevated luminance contrast thresholds in a steady pedestal paradigm, indexing magnocellular function, but not in a pulsed pedestal paradigm, reflecting typical parvocellular function.

Accounts of impaired magnocellular or dorsal stream functioning suggest general, pervasive difficulties in all aspects of motion processing in autism. As reviewed above (Section 1.5), it is clear that this is not the case. At the extreme, it has been shown that some areas of motion processing are *enhanced* in autism (Chen et al., 2012; Foss-Feig et al., 2013), which is difficult to reconcile with impaired magnocellular or dorsal stream functioning. It has also been recognised that the distinction between pathways is a potentially misleading oversimplification (Braddick et al., 2000; de Haan and Cowey, 2011; Kravitz, Saleem, Baker, & Mishkin, 2011). In particular, de Haan and Cowey (2011) argued that there is extensive cross-talk between dorsal and ventral streams, and that the concept of a unitary dorsal stream is false (see also Kravitz et al., 2011). Instead, de Haan and Cowey argue in favour of a distributed network system. Perhaps, then, the dorsal stream hypothesis is not a useful concept for understanding atypical visual processing in autism and other developmental conditions.

Similarly, the distinction between magnocellular and parvocellular pathways is not clear-cut. The ventral stream receives input from both magnocellular and parvocellular pathways (Nealey & Maunsell, 1994) and so atypical magnocellular functioning might impact on both tests of dorsal and ventral stream functioning. Furthermore, Goodbourn et al. (2012) showed that there is low consistency in typical observers between four tasks purporting to assess magnocellular functioning, and hence these tasks cannot be thought of as general measures of magnocellular function. This is important given that researchers often use one test to assess magnocellular function in autism in isolation (e.g., Greenaway et al., 2013; Pellicano et al., 2005). If these measures are not assessing a common underlying magnocellular function, it is likely that discrepancies will arise across studies. Overall, it appears that a more nuanced account may be required to understand the complex pattern of motion processing abilities in autism than those relying on simplified distinctions between magnocellular/dorsal and parvocellular/ventral streams.

1.6.2 Local versus global and complexity accounts

Two of the most consistently reported motion processing impairments in autism are biological and coherent motion perception, as reviewed above (Sections 1.5.1 and 1.5.2). They have in common that they require the integration of local motion cues (i.e., motion information from individual dots) into an overall, global percept. Conversely, individuals with autism tend to show typical or enhanced performance on tasks that do not require integration of local motion cues (e.g., Bertone, Mottron, Jelenic, & Faubert, 2003, 2005; Pellicano et al., 2005). Impaired global motion processing is consistent with the Weak Central Coherence (WCC) account of autism (Frith, 1989; Frith & Happé, 1994), which posits that individuals with autism have difficulties in seeing the higher-level ‘whole’, and instead focus on details, such as tiny particles of dust (Bogdašina, 2003).

A related theory is the Enhanced Perceptual Functioning (EPF) account (Mottron & Burack, 2001; Mottron, Dawson, Soulières, Hubert, & Burack, 2006) which also recognises that individuals with autism show a more locally biased perceptual style than typical individuals. However, in contrast to the WCC account, the EPF model does not posit a weakness in global processing. In support of this model, many researchers have failed to find evidence of a global deficit (Plaisted, Dobler, Bell, & Davis, 2006; Plaisted, Saksida, Alcántara, & Weisblatt, 2003; Plaisted, Swettenham & Rees, 1999; Mottron, Burack, Iarocci, Belleville, & Enns, 2003; L. Wang, Mottron, Peng, Berthiaume, & Dawson, 2007). Instead, the EPF account suggests that local processing is enhanced, which means that processing is generally biased towards the local level. Plaisted's (2000, 2001) Reduced Generalisation Theory (RGT) proposes that individuals with autism exhibit heightened processing of the unique features of a stimulus, but may not draw information together as they do not recognise similarities between stimuli. Reflecting these accounts, an updated version of the WCC account shifted towards a superiority in local processing rather than a deficit in global processing (Happé & Frith, 2006). However, Happé and Booth (2008) later suggested that the idea of a global deficit should be revisited.

The appeal of local versus global theories is that they have the potential to explain autistic perception in both static and dynamic tasks, as opposed to the dorsal stream hypothesis. In particular, it might explain why elevated thresholds have been reported in both form and motion coherence tasks when the task demands are adequately matched (Spencer & O'Brien, 2006; Tsermentseli et al., 2008), and why individuals with autism may be less sensitive to global but not local form information in radial frequency patterns (Grinter et al., 2010). Likewise, Chen et al. (2012) suggested that enhanced local processing could explain their finding of increased sensitivity to speed information in adolescents with autism. However, speed discrimination requires integration over space and time, and involves higher-order brain regions generally implicated in integrating local motion signals, such as MT/V5 (see Section 1.4.1). It is therefore not clear how a local processing bias would facilitate speed discrimination in those with autism, and furthermore, why such facilitation would be manifest only at specific ISIs. This study highlights a general challenge for applying WCC and EPF accounts, in how to define "local" and "global" processing. Importantly, we need to avoid circularity, by suggesting that tasks in which autistic individuals display elevated thresholds are global, and that tasks in which they show unimpaired or enhanced performance are local. A further challenge for local versus global accounts is that tasks purportedly measuring global processing share little common variance (Milne & Szczerbinski, 2009; Wagemans, Van der Hallen, Chamberlain, Van de Cruys, & de-Wit, 2014), which may be because they are limited by distinct component processes (de-Wit & Wagemans, in press; Wagemans et al., 2014). As noted for the distinction between magnocellular/dorsal and parvocellular/ventral streams (Section 1.6.1), a dichotomy between local and global processing may be too simplistic to fully capture autistic perception.

A related distinction has been proposed in the complexity account of autistic perception (Bertone, Mottron, & Faubert, 2005; Bertone, Mottron, Jelenic, & Faubert, 2003, 2005; see also Minshew, Goldstein & Siegel, 1997). According to this account, individuals with autism show typical or enhanced levels of processing for simple stimuli, and show elevated thresholds for more complex stimuli. This account can explain why autistic individuals show impaired second-order motion perception but typical perception of first-order motion stimuli (Bertone et al., 2003), and unimpaired flicker contrast sensitivity but elevated motion coherence thresholds (Pellicano et al., 2005). However, as noted for local versus global accounts, it is difficult to define "simple" and "complex". Bertone, Mottron, Jelenic, and Faubert (2003, 2005) suggested that complex stimuli require extrastriate integrative mechanisms, reflecting the definition for "global" processing. However, just because a task involves extrastriate regions, it does not necessarily mean that performance in the task is being limited by processing in these areas (Dakin & Frith, 2005; Kogan & Chaudhuri, 2005). The complexity account has also been weakened by evidence of elevated thresholds for purportedly “simple” static tasks, such as colour perception (Franklin et al., 2008, 2010) and luminance increment perception (Greenaway et al., 2013). However, there is little evidence for elevated thresholds for “simple” stimuli in motion processing in autism, and so the complexity account may still provide a good heuristic in this case. However, it is still difficult to explain why some authors report difficulties in “complex” motion tasks, while others do not (see Table 1.1), unless suggesting that other stimulus parameters and differences in participant characteristics are contributing.

Attempts have been made to link local versus global and complexity accounts to the neural level. Samson et al. (2012) conducted a meta-analysis of neuroimaging studies for visual tasks and reported that autistic individuals had more activity in brain regions associated with visual processing and less activity in frontal regions compared to typical controls. They suggested that this pattern could lead to enhanced processing of low-level visual information, as proposed in the EPF model. As summarised in Section 1.1.4, much research suggests that brain connectivity is atypical in autism. Specifically, it has been suggested that the brains of autistic individuals have weak long-range connectivity, possibly in conjunction with local overconnectivity (see Maximo, Cadena, & Kana, 2014, for review). Such a pattern of atypical connectivity may lead to inefficiencies in integrating information across brain areas, which is thought to be required for processing global or complex stimuli, but not for processing local or simple stimuli (Bertone & Faubert, 2006). However, there is little empirical evidence relating measures of connectivity to motion processing performance within the same individuals. One study that aimed to do this showed no differences between autistic and TD adolescents in functional connectivity between dorsal areas V1 and V5 during a coherent motion task (Brieber et al., 2010). The authors suggested that atypical motion coherence processing may instead reflect atypical lateral connectivity within low-level visual areas, rather than between visual areas. McKay et al. (2012) showed reduced connectivity between temporal and parietal areas in autistic individuals during a biological motion task. It is therefore important to specify precisely the type of altered connectivity that leads to atypical motion processing in autism.

1.6.3 Temporo-spatial processing disorders

As we have seen, there is a fairly widespread consensus that individuals with autism integrate information atypically. Gepner and colleagues suggested that such atypicalities are found specifically when individuals with autism are required to integrate information across time and space, in their ‘temporo-spatial processing disorders hypothesis’ (Gepner & Féron, 2009; Gepner, Lainé, & Tardif, 2005, 2010). Such difficulties might disrupt the ability to perceive sensory events online, in turn leading to the perception of the environment changing too rapidly for individuals with autism (Gepner & Féron, 2009), which is consistent with autobiographical reports from autistic adults (Grandin, 1995; D. Williams, 1999). A prediction arising from the temporo-spatial processing disorders hypothesis is that individuals with autism should have particular difficulties in processing fast-moving stimuli, when the temporo-spatial integration requirements are greater. In line with this prediction, Gepner et al. (2001) showed that slowing down dynamic face stimuli improved emotion recognition for those with autism. Additionally, Mestre et al. (2002) showed weaker oculomotor activity specifically for fast stimuli and Greffou et al. (2012) found weak postural stability specifically for high oscillation frequencies. This evidence, however, is not entirely convincing. Slowing down stimuli could simply increase the salience of important cues for individuals with autism, rather than reducing temporo-spatial processing requirements, and both Mestre et al. and Greffou et al.'s studies involve the motor system as well as the visual system. These results therefore do not conclusively demonstrate atypical temporo-spatial processing of sensory information. A further challenge for the temporo-spatial processing disorders hypothesis is in explaining the reports of enhanced motion processing in autism (Chen et al., 2012; Foss-Feig et al., 2013).

A related account is that individuals with autism require a longer temporal window for motion processing, due to atypical integration specifically in the temporal domain (C. E. Robertson et al., 2012). As reviewed in Section 1.5.2, C. E. Robertson et al. (2012) found that autistic adults had elevated motion coherence thresholds specifically for short (200 ms) but not long stimuli (400 ms and 1500 ms; see also C. E. Robertson et al., 2014). R. A. O. Davis et al. (2006) reported precisely the opposite pattern in a group of children with autism (see Table 1.1), which could suggest that temporal integration differs between children and adults with autism. However, R. A. O. Davis et al.'s study used a small sample (autism: *n* = 9; TD: *n* = 9), making it difficult to draw firm conclusions. Future research is therefore required to investigate the temporal integration of motion information in children with autism.

1.6.4 Extreme male brain theory

Baron-Cohen and colleagues proposed an 'extreme male brain' theory of autism, where they suggested that high levels of foetal testosterone lead to the development of autistic behaviours (Baron-Cohen, 2002; Baron-Cohen & Hammer, 1997; Baron-Cohen, Lutchmaya, & Knickmeyer, 2004; Baron-Cohen et al., 2014, but see also Whitehouse et al., 2012). Baron-Cohen et al. argued that autistic behaviours include extreme 'male' traits such as systemizing, and reduced 'female' traits, such as empathising. Atypical levels of foetal testosterone may alter later brain development, potentially leading to atypical motion processing in autism. One indicator of foetal testosterone is the ratio of second to fourth finger length (2D:4D), with longer fourth fingers than second fingers reflecting higher levels of foetal testosterone (J. T. Manning et al., 1998). Indeed, Milne et al. (2006) showed that 2D:4D ratios were related to motion coherence thresholds in a group of children with autism, suggesting that high levels of testosterone prenatally might lead to difficulties in motion processing.

However, as Milne et al. (2006) note, this conclusion is highly speculative, as no direct link has been established between foetal testosterone and 2D:4D ratio. Furthermore, the evidence for gender differences in motion processing is not well-established, making it unclear how atypical motion processing could be explained by an extreme male brain. Kramer, Ellenberg, Leonard, and Share (1996) actually showed that males had a bias towards more global processing than females, which contrasts directly with the suggestion that individuals with autism have a bias for the local level (see Section 1.6.2). Falter, Plaisted, and Davis (2008) failed to find significant differences in 2D:4D ratios between children with autism and TD children matched in IQ, and found no conclusive evidence that 2D:4D ratios were related to visuospatial processing ability. More recently, Auyeung et al. (2012) investigated relationships between foetal testosterone and visuospatial task performance, and found only a relationship with Embedded Figures performance and not mental rotation or ball-targeting. Given that gender differences have been more reliably reported in visuospatial processing tasks than in motion perception (e.g., Aleman, Bronk, Kessels, Koppeschaar, & van Honk, 2004; Falter, Arroyo, & Davis, 2006), it seems unlikely that the extreme male brain theory will be able to account for motion processing atypicalities in autism.

1.6.5 Neural noise accounts

Simmons et al. (2009) argued that the complex pattern of visual abilities in autism could be explained by higher levels of internal noise (i.e., increased neural variability) compared to TD individuals. Under most cases, increased levels of noise would lead to degraded detection and discrimination performance, explaining the many reports of elevated thresholds in motion processing tasks. Indeed, Dakin and Frith (2005) suggested that performance in motion coherence tasks could be limited by increased neural noise in autism. However, in certain cases, increased levels of noise could be beneficial, leading to enhanced performance, through a nonlinear phenomenon called stochastic resonance (McDonnell & Abbott, 2009; McDonnell & Ward, 2011; Wiesenfeld & Moss, 1995). Therefore, this theory has the potential to explain both decreased and increased sensitivity to visual information in autism.

Psychophysical evidence for increased internal noise in autism is relatively sparse, but neuroimaging experiments have provided support. Milne (2011) showed that the EEG responses of young people with autism were more variable trial-by-trial than those of TD children. Similarly, Dinstein et al. (2012) reported increased trial-by-trial variability in evoked blood oxygenation level-dependent (BOLD) responses using fMRI. It has also been suggested that there are greater spontaneous fluctuations in neural activity in the brains of autistic people than typical individuals at rest (Velázquez & Galán, 2013). Possible causes of increased internal noise include excessive cortical connections (Belmonte et al., 2004; see also Minshew & Williams, 2007, for review), atypical minicolumn structure (Casanova, Buxhoeveden, Switala, & Roy, 2002), altered synaptic activity (Bourgeron, 2009; Garber, 2007), and an imbalance between excitatory and inhibitory function (Rubenstein & Merzenich, 2003).

However, in direct contrast to Simmons et al.'s account, it has been suggested that the visual abilities of autistic individuals could instead be attributed to *reduced* internal noise (G. Davis & Plaisted-Grant, in press; Greenaway et al., 2013). G. Davis and Plaisted-Grant (in press) argued that reduced noise in individuals with autism is not inconsistent with increased trial-by-trial variability in EEG and fMRI recordings (Dinstein et al., 2012; Milne, 2011), as noise in small-scale networks may be negatively related to 'global' noise measured by EEG and fMRI. G. Davis and Plaisted-Grant (in press) proposed three main consequences of reduced noise in small-scale neural networks. First, they suggested that reduced neural noise would affect detection and discrimination, leading to enhanced performance in tasks such as visual search (e.g., Plaisted, O'Riordan, & Baron-Cohen, 1998a). Second, they argued that low noise would reduce shifts between network states in individuals with autism, leading to reduced perceptual switching in tasks such as binocular rivalry (e.g., C. E. Robertson, Kravitz, Freyberg, Baron-Cohen, & Baker, 2013). Third, G. Davis and Plaisted-Grant proposed that reduced noise might lead to heightened discriminability of representations but reduced generalisation, as also proposed in RGT (Plaisted, 2001; see Section 1.6.2).

Specifically, G. Davis and Plaisted-Grant (in press) related their account of reduced neural noise to previous findings concerning motion processing in autism. They proposed that autistic observers have an enhanced representation of individual directions in a stimulus, but poor integration of these stimuli. Therefore, individuals with autism should demonstrate typical or enhanced performance when all stimulus elements move in the same direction. Yet, they should show elevated thresholds in tasks involving integration, such as motion coherence tasks (see Section 1.5.2).

The divergence between increased and reduced noise accounts may be due to the fact that our understanding of the role of noise in typical development is limited. On the one hand, it is conceivable that neural noise reduces with age, leading to increased sensitivity to sensory information (Buss, Hall, & Grose, 2006). On the other hand, it has been suggested that noise is beneficial in development, helping children to explore multiple states and to adapt to different situations (McIntosh, Kovacevic, & Itier, 2008; Vakorin, Lippe, & McIntosh, 2011). Indeed, noise can arise from many different sources (Faisal, Selen, & Wolpert, 2008), and may have different effects in different brain areas. Noise accounts therefore have the potential to explain the very complex pattern of atypical visual processing in autism. However, it is currently unclear what effect atypical noise at different levels has on motion processing, and hence clear, testable predictions for autistic perception are lacking.

1.6.6 Reduced top-down influences

It has been suggested that the visual perception of individuals with autism might be less affected by top-down influences, such as prior knowledge (Mitchell, Mottron, Soulières, & Ropar, 2010; Ropar & Mitchell, 2002) and attentional modulation (at least for dynamic stimuli; Greenaway & Plaisted, 2005) than in typical individuals. These ideas have recently been incorporated within a Bayesian framework, in a new theory of autistic perception (Pellicano & Burr, 2012). According to the Bayesian framework, perception is influenced both by incoming sensory signals and prior knowledge about the world. Pellicano and Burr (2012) suggested that individuals with autism may be less influenced by prior knowledge about the world (i.e., they have ‘hypo-priors’). As a result, autistic perception is more heavily influenced by incoming sensory signals, and individuals with autism see the world more veridically. Initial experimental support for this account comes from a study of individuals with high levels of autistic traits using a signal detection theory framework (Skewes et al., 2014).

While no research has yet explicitly tested whether the theory can account for motion processing abilities in individuals with autism, the theory makes specific, testable predictions. In particular, the theory suggests that motion perception in individuals with autism will be less influenced by prior knowledge and therefore less susceptible to biases. It has been shown in typical adult observers that motion perception is influenced by a prior belief that objects are likely to be moving slowly, because degrading the quality of sensory information leads to objects appearing to move more slowly (Weiss, Simoncelli, & Adelson, 2002). Furthermore, Verghese and McKee (2006) have suggested that a prior for smooth motion leads to elevated speed discrimination thresholds when objects appear to cross a boundary. Pellicano and Burr (2012) predict that individuals with autism might be less susceptible to these biases. Related models have been proposed which differ in their precise mechanisms, but make similar predictions of less biased perception (Brock, 2012; van de Cruys, de-Wit, Evers, Boets, & Wagemans, 2013; van de Cruys et al., 2014). It is therefore an interesting avenue for future research to assess whether motion perception is more veridical in individuals with autism compared to TD individuals.

1.6.7 Summary of theories of atypical motion processing in autism

In Section 1.5, I showed that the field of motion processing in autism is clouded by discrepant findings. It is perhaps understandable, then, that there is no consensus as to what theory accounts for atypical motion processing in autism. Both the dorsal stream vulnerability and temporo-spatial processing disorders hypotheses fail to explain the few reports of enhanced motion perception in autism (Chen et al., 2012; Foss-Feig et al., 2013), as they propose a deficit in motion processing. In contrast, local vs. global and complexity accounts allow for both areas of impaired and unimpaired (or even enhanced) perception, although defining terms such as “local”, “global” and “complex” is problematic. Noise accounts are promising yet no studies have yet related measures of noise to motion processing performance. Overall, it appears that a nuanced account may be required to incorporate the wide range of results reported.

1.7 Conclusions

Despite much research investigating motion processing in individuals with autism, the results are inconsistent and no current theory provides a full account of the data. Yet, understanding how children with autism process motion information is critical in understanding how they perceive and interpret the world around them, which can have a great impact on their everyday lives. This thesis therefore aims better to characterise motion processing in children with autism, and in particular, to address why children with autism have difficulties with some motion processing tasks, but not others.

Much research has focused on direction processing in autism, but relatively little research has addressed the perception of speed information in autistic individuals. Furthermore, while there is evidence for differential developments of sensitivity to slow and fast motion in typical development, this has not been systematically tested in autism. Therefore, in Chapter 2, I investigate whether children with autism have atypical speed discrimination thresholds for slow- and fast-moving stimuli. Discrepant results have arisen from the motion coherence paradigm, which I have suggested may be due to differences in stimulus parameters. Therefore, Chapter 2 will also address whether sensitivity to coherent motion information might similarly depend on stimulus speed in children with autism. In Chapter 3, I investigate whether children with autism appear to experience difficulties processing speed-related information in everyday life using a parent-report questionnaire, and investigate whether these difficulties are related to psychophysical task performance.

In Chapters 4 and 5, I aim to elucidate the factors underlying reduced coherent motion sensitivity in autism. While it is often assumed that elevated motion coherence thresholds reflect reduced integration of motion signals (see Section 1.6.2), it is also possible that reduced sensitivity to coherent motion could arise from imprecision in estimating local directions (Dakin & Frith, 2005). In Chapters 4 and 5, I aim to quantify local and global factors contributing to direction integration performance in TD children and children with autism, by using an equivalent noise direction integration task (Bex et al., in prep; Dakin, Mareschal, & Bex, 2005; Tibber, Kelly, Jansari, Dakin, & Shepherd, 2014) alongside a traditional motion coherence task. It is not yet known what underlies the protracted development of coherent motion sensitivity in typical development (see Section 1.4.2). Chapter 4 therefore aims to characterise the local and global contributions to coherent motion processing in TD children aged between 5 and 11 years of age. This study serves as a developmental baseline to inform the study presented in Chapter 5, which will compare children with autism to TD children.

Chapter 6 then aims to reconcile discrepant motion coherence results by considering whether the limited lifetime of dots (i.e. the duration of each dot within a stimulus) contributes to elevated motion coherence thresholds in autism. Finally, in Chapter 7, I summarise my findings, discuss their importance within the context of current theoretical accounts, and suggest that we need a more nuanced account of motion processing abilities in autism.

2 Sensitivity to speed and coherent motion information at slow and fast speeds in children with autism

2.1 Introduction

As reviewed in Chapter 1, the ability to process speed information has so far received little attention in autism. Yet, there are theoretical and empirical reasons to suggest that this ability might be atypical in autistic individuals. Based on the dorsal stream hypothesis (Braddick et al., 2003), it would be predicted that children with autism have difficulties in processing speed information, and according to the temporo-spatial processing disorders hypothesis (Gepner & Féron, 2009), these differences should be particularly pronounced for fast-moving stimuli. In line with these hypotheses, there is experimental evidence suggesting that individuals with autism process speed-related information atypically (Gepner et al., 2001; Greffou et al., 2012; Mestre et al., 2002; but see also Koldewyn et al., 2013).

However, only one study has directly tested speed perception in autism. Chen et al. (2012) presented pairs of unlimited lifetime random dot stimuli using a fast (5.25 deg/sec) reference speed to adolescents with autism aged 13 to 18 years and typically developing (TD) adolescents of similar age. The stimuli were separated either by a short (500 ms) or long (3000 ms) interstimulus interval (ISI). The autistic individuals had comparable thresholds to the TD individuals when the ISI was short, but *lower* thresholds when the ISI was prolonged to 3000 ms. Chen et al. interpreted these findings as evidence of *enhanced* local processing of dynamic information in autism, which is manifest only at longer ISIs due to the requirement for a prolonged temporal window for visual processing in individuals with autism.

The dot stimuli used in Chen et al.'s (2012) study were not limited in their lifetime, however, which meant that participants could conceivably have performed the task by tracking individual dots. It remains to be seen whether individuals with autism would still show unimpaired – or enhanced – sensitivity to speed differences when limited lifetime stimuli are used, where it might be advantageous to integrate over multiple dots. Furthermore, given evidence of differentially developing systems for processing slow and faster speeds (C. Manning et al., 2012), it remains unclear whether these systems are similarly affected in children with autism. The temporo-spatial processing disorders hypothesis posits that individuals with autism have particular difficulties processing fast speeds. Yet, it is also possible that the processing of slow speeds, which develops more gradually and matures later, may be particularly susceptible to atypical development.

Another dorsal stream function that has been more extensively studied in autism is the ability to perceive coherent motion amidst random motion. Studies investigating coherent motion perception in autism have yielded discrepant findings, which may, at least in part, be attributable to differences in task and stimulus parameters across studies (see Section 1.5.2 and Table 1.1). If individuals with autism process speed-related information atypically, this might also have an effect on coherent motion perception. This study therefore sought to investigate whether the speed of coherent motion stimuli is a factor contributing to the extent of differences between autistic and TD individuals. Elevated motion coherence thresholds in autism have been reported for a range of different stimulus speeds, and there does not appear to be a systematic relationship between the stimulus speed and presence of group differences (see Table 1.1). Yet, comparing the effect of stimulus speed across studies is complicated by variability in many other stimulus parameters such as duration, stimulus size and density. It is therefore important to assess directly the effect of stimulus speed in the same participants, while holding other stimulus parameters constant. Furthermore, existing studies of motion coherence in autism have focused on mid-to-fast speeds (see Table 1.1) leading to the possibility that motion coherence thresholds may be disproportionately affected for slower moving stimuli.

Speed discrimination and motion coherence abilities involve similar brain areas in the adult brain, and may be processed in similar ways (see Section 1.4.1). However, the relationship between speed discrimination and motion coherence abilities during development has not been empirically studied. Chen et al. (2012) found no relationship between speed discrimination thresholds and motion coherence sensitivity in their autistic adolescents. However, Chen et al.'s stimuli were not well-equated between tasks, with two stimuli being presented successively in the speed discrimination task, and only a single stimulus being presented in the motion coherence task. Ultimately, a better understanding of the relationship between speed and motion coherence sensitivity in typical and atypical development may help inform our understanding of how speed and global direction are processed in the brain.

In this study, a speed discrimination task and a motion coherence task were administered at two speed conditions (slow: 1.5 deg/sec, and fast: 6 deg/sec) to children with autism and age- and ability-matched TD children. This manipulation allowed me to address two key aims. First, I investigated whether children with autism have atypical speed discrimination thresholds, and if so, whether atypicalities are more pronounced for slow or fast speeds. Second, I assessed whether differences in coherent motion sensitivity between autistic and non-autistic children depend on stimulus speed. The presentation of well-matched speed discrimination and motion coherence tasks to the same group of children allowed me to also assess relationships, if any, between these two abilities in typical development and in children with autism. Finally, I was interested in how atypical motion processing might be related to atypical motor skills in autism (Milne et al., 2006; Price et al., 2012). To this end, parents of children with autism were asked to complete a questionnaire about their child's motor abilities (Developmental Coordination Disorder Questionnaire 2007, DCDQ'07; Wilson, Kaplan, Crawford, & Roberts, 2007). Parents also completed a questionnaire asking about their child's ability to process speed-related information in daily life – the results of which will be fully analysed in Chapter 3.

2.2 Method

2.2.1 Methodology

Throughout this thesis, children's sensitivity to motion information is quantified using psychophysical methods. Psychophysical methods offer the opportunity to study perception by systematically varying the physical properties of a stimulus and recording their effect on an observer's behaviour (S. S. Stevens, 1957). Measures of sensory thresholds can be obtained, as either the intensity required for a stimulus to be just detectable, or the difference between two stimuli necessary for them to be just noticeably different (D. M. Green & Swets, 1966).

There are multiple threshold estimation techniques available to psychophysicists, which can be broadly separated into non-adaptive and adaptive methods. Non-adaptive methods, such as the Method of Constant Stimuli, test responses at predefined stimulus levels, whereas adaptive methods use previous responses to guide which stimulus levels are presented next, in order to 'home in' on the threshold. Adaptive methods have increased efficiency as they place trials at stimulus levels that will be most informative of the threshold (Kingdom & Prins, 2010). Thus adaptive techniques allow reliable threshold estimates to be obtained in fewer trials than non-adaptive methods (Macmillan & Creelman, 1991), and are therefore appealing when testing children who may get bored and lose attention easily. Yet, adaptive techniques may be particularly affected by attentional lapses, especially when such lapses occur early on in the testing session (Kingdom & Prins, 2010). Lapses are likely to be more frequent in children than adult observers (e.g., Wightman & Allen, 1992; Wightman, Allen, Dolan, Kistler, & Jamieson, 1989) which might lead to an overestimation of thresholds (i.e., underestimated sensitivity) in children.

Developmentally appropriate psychophysical methods were developed for use in the studies reported in this thesis. Thresholds were measured using an adaptive method, QUEST (Watson & Pelli, 1983), which places each trial at the current most probable Bayesian estimate of the threshold. This efficient method allowed the use of fewer trials compared to non-adaptive methods, whilst also avoiding the difficulty of selecting appropriate predefined stimulus values (which is particularly difficult given the between-participants variability in thresholds in young children, e.g., C. Manning et al., 2012). The QUEST procedure can either be terminated when a confidence interval for the location of the threshold has reached a specified size, or alternatively, after a fixed number of trials (Kingdom & Prins, 2010). The latter option was chosen here in order to make the length of testing sessions predictable, which was deemed particularly important as the majority of testing took place within schools. On the termination of the QUEST procedure, threshold values can be obtained in one of two ways (Kingdom & Prins, 2010). First, QUEST can return the most probable Bayesian estimate of the threshold at the end of the procedure using the mean or mode of the posterior probability density function. Second, a psychometric function can be fit to all of the data points collected during testing. The latter option was chosen for this study. In order to adequately sample the psychometric function, random jitter was added to the testing intensities suggested by the QUEST procedure (Watson & Pelli, 1983).

It was important to ensure that children's attention and motivation would be maintained throughout the experiment, both to make it an enjoyable experience for participants and to prevent lapses in attention affecting the threshold obtained. Abramov et al. (1984) developed a paradigm whereby they measured visual functioning in young children through a series of space-themed "games". They reported that good thresholds could be obtained in a short amount of time as children were receptive to instructions and attentive. Similarly, C. Manning et al. (2012) measured speed discrimination thresholds successfully in children as young as 5-years-old using a space-related "game" with three "levels". The current experimental tasks used "games" based on C. Manning et al.'s method (see Section 2.2.5). Despite considerable efforts to maintain children's engagement and motivation, attentional lapses are not entirely preventable, particularly in young children or children with attentional difficulties, including those with autism (Matson, Rieske, & Williams, 2013). Therefore, inattentiveness was estimated using the proportion of incorrect responses to 'easy' catch trials (Kingdom & Prins, 2010; Treutwein, 1995).

2.2.2 Participants

Thirty-six children with autism and 41 TD children aged between 7 and 14 years were recruited from mainstream schools, special schools, autism provisions and community contacts in England. All children with autism had previously received an independent clinical diagnosis of autism or autism spectrum disorder according to ICD-10 criteria (World Health Organisation, 1993). Five children with autism were removed from the dataset as their IQ scores indicated intellectual impairment (verbal IQ [VIQ] < 70 and/or performance IQ [PIQ] < 70) as assessed by the Wechsler Abbreviated Scales of Intelligence (WASI; Wechsler, 1999; see Section 2.2.3).

Parents or caregivers (henceforth referred to as ‘parents’) completed the Social Communication Questionnaire (SCQ; Rutter, Bailey, & Lord, 2003; see Section 2.2.3) and children with autism were administered the Autism Diagnostic Observation Schedule-Generic (ADOS-G; Lord, Rutter, DiLavore, & Risi, 1999). Only those who scored above threshold for an autism spectrum condition on at least one of these measures were included in this study (see Corsello et al., 2007, for the combined use of these measures). Two children with autism were removed from the dataset as they did not meet the autism spectrum cut-off on either measure. All TD children scored below the cut-off for autism on the SCQ (Rutter et al., 2003) and had no diagnosed developmental conditions, as reported by parents. Snellen acuity charts were used to confirm normal or corrected-to-normal visual acuity, using optical corrections where necessary. Normal acuity was defined as a binocular acuity of 6/9 or better for children aged 7 to 8 years (because acuity is still maturing in this age range; Adams & Courage, 2002; Bradley & Freeman, 1982) and 6/6 or better for older children. One child with autism and 2 TD children were removed from the dataset as they did not meet this criterion.

Twenty-eight children with autism (*M* = 10 years; 3 months, range 7;2 – 13;9, 3 females) were therefore included in the final dataset. Thirty-two TD children (*M* = 10 years; 5 months, range 7;0 - 14;1, 6 females) were selected to match the autism group in terms of chronological age, $t(57.00) = .18$, $p = .86$[2], PIQ, $t(58) = 1.32$, $p = .19$, and VIQ, $t(58) = 1.69$, $p = .10$. Participant demographics of children included in the final dataset are provided in Table 2.1.

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[2] Throughout this thesis, corrected degrees of freedom (*df*) are provided where Levene’s test of homogeneity of variance was violated.

Table 2.1 Participant characteristics

Characteristic	*Children with autism*	*Typically developing children*
n	28	32
Gender (*n* males: *n* females)	25:3	26:6
Age (years;months)		
Mean (SD)	10;3 (1;8)	10;5 (2;3)
Range	7;2 – 13;9	7;0 – 14;1
Verbal IQ		
Mean (SD)	101.64 (12.26)	106.88 (11.74)
Range	75 – 134	79 – 129
Performance IQ		
Mean (SD)	103.46 (14.73)	108.38 (13.98)
Range	79 – 133	84 – 132
Full-scale IQ		
Mean (SD)	102.93 (12.89)	108.59 (11.77)
Range	77 – 130	85 – 127
Mother’s age on leaving full-time education		
Mean (SD)	20.65 (3.58)	21.31 (4.23)
Range	16 – 30	16 – 34
SCQ score		
Mean (SD)	24.22 (8.93)	3.00 (2.49)
Range	5 – 39	0 – 9
ADOS communication		
Mean (SD)	3.18 (1.61)	
Range	0 – 7	
ADOS social interaction		
Mean (SD)	7.54 (2.81)	
Range	3 – 12	
ADOS stereotyped behaviours/restricted interests		
Mean (SD)	1.93 (1.56)	
Range	0 – 5	
DCDQ’07 control during movement		
Mean (SD)	15.88 (7.98)	
Range	6 – 39	
DCDQ’07 fine motor skills		
Mean (SD)	8.54 (3.70)	
Range	4 – 16	
DCDQ’07 general coordination		
Mean (SD)	11.23 (4.79)	
Range	5 – 20	

Note: DCDQ’07 = Developmental Coordination Disorder Questionnaire 2007 (Wilson et al., 2007); ADOS = Autism Diagnostic Observation Schedule (Lord et al., 1999). N.b. DCDQ’07 and ADOS-G data were not collected for typically developing children.

As reviewed in Section 1.1.3, co-occurring disorders are common in individuals with autism. Accordingly, 9 participants with autism had additional diagnoses of developmental conditions, the most common of which was attention deficit/hyperactivity disorder (AD/HD; *n* = 8). Parents of two of the participants with autism and AD/HD also reported one or more additional conditions (including tic disorders and oppositional defiant disorder). One participant with autism had a diagnosis of dyslexia. Participants with additional diagnoses were retained in the dataset as it is difficult to tease these developmental conditions apart (Section 1.1.3), and as diagnostic practices may vary. Moreover, inclusion of these participants maintained statistical power.

Parents were given a brief background questionnaire which included items relating to ethnic group and indicators of socioeconomic status (SES), such as the mother's age on leaving full-time education (American Psychological Association Task Force on Socioeconomic Status, 2007). Twenty-seven parents of children with autism and 28 parents of TD children in the final dataset responded to these items. The majority of parents reported being White British, both in the autism group (n = 24) and TD group (n = 23). Other ethnic backgrounds reported in the autism group were Mixed White and Asian (n = 1), Pakistani (n = 1) and Latin American (n = 1), and in the TD group, White Irish (n = 1), American (n = 1), Bangladeshi (n = 1), Caribbean (n = 1) and Latin American (n = 1). The mother's age on leaving full-time education did not differ between the autism group and TD group, $t(50) = .60$, $p = .55$ (see Table 2.1 for scores).

2.2.3 Standardised measures

Wechsler Abbreviated Scales of Intelligence (WASI)

The WASI (Wechsler, 1999) is a brief measure of intelligence containing four subtests: vocabulary, block design, similarities and matrix reasoning. The vocabulary and similarities subtests are used to derive a measure of VIQ, and the block design and matrix reasoning subtests are combined to estimate PIQ. All subscales together form the measure of full-scale IQ (FSIQ). The WASI has been standardised for use on individuals aged 6 to 89 years.

Social Communication Questionnaire (SCQ)

Parents of children with autism and TD children completed the Lifetime Version of the SCQ (Rutter et al., 2003) which is a 40-item questionnaire used to screen for autistic-like behaviours throughout a child's developmental history. A cut-off score of 15 has been shown to be effective in discriminating between those with and without autism spectrum disorders (Chandler et al., 2007). The SCQ was returned by 27 parents of children included in the autism group, and 29 parents of children included in the TD group. SCQ data were not available for one child with autism who had recently been taken into care, because the caregiver could not report on the child's earlier development.

Autism Diagnostic Observation Schedule-Generic (ADOS-G)

Children with autism were administered the ADOS-G (Lord et al., 1999), which is a semi-structured, standardised observation tool that is often used when diagnosing individuals with autism. It contains structured activities and materials to provide a context in which to observe social interactions, communication, and other relevant behaviours. Each item is scored between 0 (indicating behaviours that are in line with developmental norms) and 3 (indicating atypical behaviours related to an autism diagnosis). A scoring algorithm is followed in order to derive scores for communication, reciprocal social interaction, combined communication and social interaction, and stereotyped behaviours and restricted interests. There are four distinct modules relating to developmental and language levels: Module 1 is for use with individuals who use no expressive language or only single words; Module 2 is for individuals who use phrase speech; Module 3 is for children and adolescents with fluent speech, and Module 4 is for adolescents and adults with fluent speech. In this study, participants completed either Module 3 (*n* = 23) or Module 4 (*n* = 5) as all participants had fluent speech. In these modules, the cut-off for an autism spectrum disorder is 2 in the communication subscale, 4 in the reciprocal social interaction subscale, and 7 in the combined communication and social interaction total.

Developmental Coordination Disorder Questionnaire (DCDQ'07)

Parents of children with autism completed the DCDQ'07 (Wilson et al., 2007) in order to investigate the potential relationship between atypical motion perception and motor skills in autism (Milne et al., 2006; Price et al., 2012). The DCDQ'07 is a 15-item parent questionnaire designed to identify Developmental Coordination Disorder (DCD) in children aged 5 to 15 years. Parents were asked to compare their child's performance in a range of motor skills to that of his/her peers, rating each item between 1 (*not at all like my child*) to 5 (*extremely like my child*). The questionnaire yields a total score between 15 and 75 and scores for three separate subscales: control during movement (between 6 and 30), fine motor skills (between 4 and 20), and general coordination (between 5 and 25). Lower scores indicate poorer motor coordination. For children aged 5 years to 7 years 11 months, a total score of 46 or under suggests that the child may have DCD. For children aged 8 years to 9 years 11 months, the cut-off is 55, and for children aged 10 to 15 years, the cut-off is 57. The DCDQ'07 was returned by 26 parents of children with autism included in the dataset.

2.2.4 Apparatus and stimuli

The stimuli were presented using MATLAB (The Mathworks Ltd.) using elements of the Psychophysics Toolbox software (Brainard, 1997; Kleiner, Brainard & Pelli, 2007; Pelli, 1997). Stimuli were displayed on a Philips 107E CRT monitor measuring 34.03 deg x 25.91 deg when viewed at a distance of 50 cm, controlled by a

Dell Precision M4600 laptop. The monitor had a frame rate of 60 Hz with a pixel resolution of 1024 x 768.

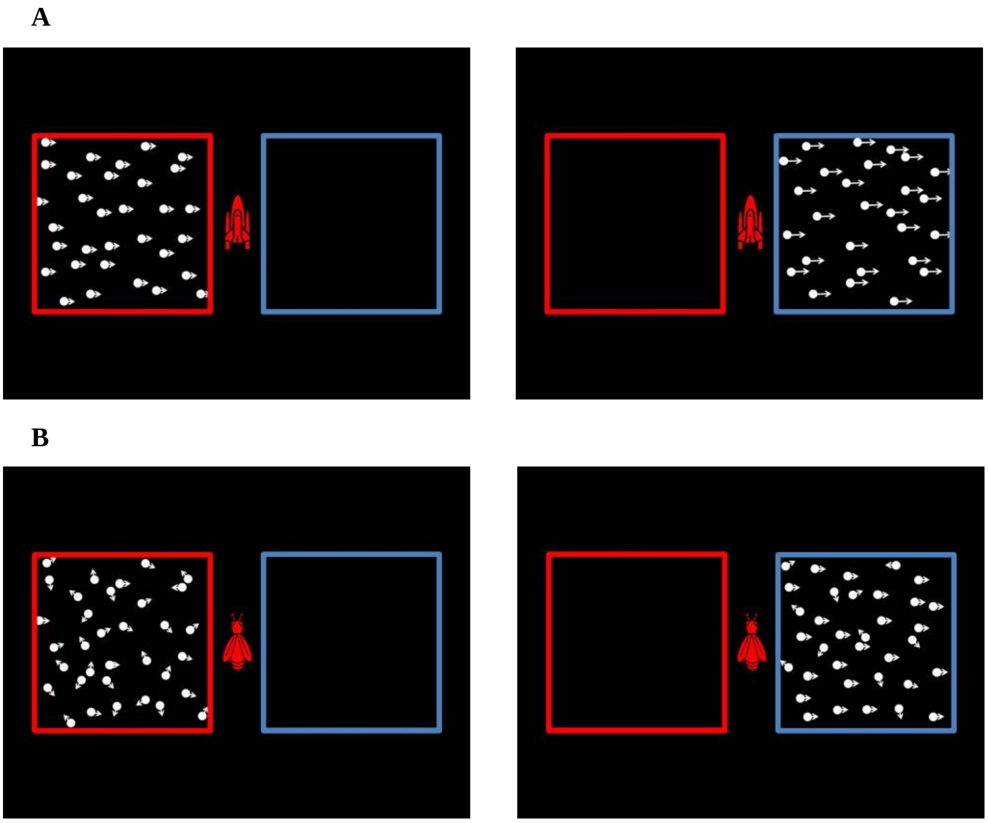


Figure 2.1 Schematic representation of stimuli presented in the speed discrimination (A) and motion coherence (B) tasks.

Arrows are for illustrative purposes only, representing the direction and speed (arrow length) of dot motion. Panel A shows the speed discrimination reference stimulus (left) in which dots are moving at 1.5 deg/sec or 6 deg/sec (slow, fast conditions) with 100% motion coherence and the speed discrimination comparison stimulus (right) in which dots are moving at a speed above that of the reference stimulus with 100% motion coherence. Panel B shows the motion coherence reference stimulus (left) in which dots are moving at 1.5 deg/sec or 6 deg/sec (slow, fast conditions) with 0% motion coherence and the motion coherence comparison stimulus (right) in which dots are moving at 1.5 deg/sec or 6 deg/sec (slow, fast conditions) with a proportion of coherently moving dots.

The screen was black with a central fixation point (1.54 deg x 3.12 deg) shaped as either a rocket or a fly for the speed discrimination and motion coherence tasks, respectively. The colour of the fixation point marked different trial events: green to prompt fixation before the trial commenced, red to signal stimulus presentation, and yellow while participants responded. There was a red square aperture (11 deg x 11 deg) to the left and a blue square aperture (11 deg x 11 deg) to the right of fixation. The stimuli were moving random dot patterns appearing for 1000 ms within either aperture (red, blue), as illustrated in Figure 2.1. In each stimulus, there were 100 white dots each measuring 0.34 deg diameter, yielding a dot density of 0.83 dots/deg^2. Each dot displayed at the beginning of a trial was randomly assigned a starting life, and had a limited lifetime of 5 monitor refreshes (~83 ms). On reaching its decay lifetime, each dot was replaced by another dot in a new random location.

2.2.5 Procedure

Children completed a speed discrimination task and a motion coherence task in each of two speed conditions: slow (1.5 deg/sec) and fast (6 deg/sec). In both tasks, a trial consisted of a pair of stimuli (a reference and comparison stimulus) presented sequentially separated by a 500 ms ISI in which the apertures and fixation point remained on screen. A stimulus in the left (red) aperture was followed by a stimulus in the right (blue) aperture, and vice versa (see Figure 2.1)

The speed discrimination task was based on C. Manning et al. (2012). The reference stimulus moved at 1.5 deg/sec or 6 deg/sec (slow, fast conditions), with the speed of the comparison stimulus varying above the reference speed. Both stimuli moved with 100% dot coherence (i.e., all dots moved in the same direction). Children were told that the red and blue apertures corresponded to the windows of red and blue rockets, respectively, and were asked to determine which rocket had “stars” travelling faster past the window. To aid motivation, children were told that they were competing against a cartoon character, “Astro”.

In the motion coherence task, both reference and comparison stimuli moved at 1.5 deg/sec or 6 deg/sec (slow, fast conditions). The reference stimulus had 0% dot coherence whereas the comparison stimulus contained a percentage of coherently moving dots. Children were told that the red and blue boxes corresponded to red and blue viewing boxes containing fireflies. The child’s task was to work out which box contained “fireflies” that seemed to be “escaping” together in the same direction. To enhance motivation, children were told that they were competing against a “camera system” monitoring the boxes.

Each task was presented in the context of a game with three levels: a combined demonstration and criterion phase (“level 1”), a practice phase (“level 2”), and a threshold estimation phase (“level 3”).

2.2.5.1 Demonstration and criterion phase.

Initial introductory phases were presented to introduce children to the speed discrimination and motion coherence “games” (see Figures 2.2 and 2.3). Next, the experimenter explained each task to children within the context of four demonstration trials. The first two of these trials were “easy”: in the speed discrimination task, the comparison speed was twice that of the reference stimulus (slow condition: 3 deg/sec; fast condition: 12 deg/sec), and in the motion coherence task, the comparison stimulus moved at 100% coherence. The next two trials were “slightly harder”, with a comparison speed 1.2 times that of the reference stimulus in the speed discrimination task (slow condition: 1.8 deg/sec; fast condition: 7.2 deg/sec) and 70% dot coherence in the motion coherence task.

Next, children were presented with up to 20 criterion trials. In the speed discrimination task, criterion trials were presented with a comparison speed of 7 deg/sec or 18 deg/sec in the slow and fast conditions, respectively. In the motion coherence task, 95% of the dots in the comparison stimulus moved coherently. All participants reached a criterion of four consecutive correct responses within 20 trials for both tasks.

The order of presentation of the reference and comparison stimulus (first or second interval) and the direction of motion (leftwards, rightwards) was randomised on each trial. Children responded either verbally (“red” or “blue”) or by pointing at the window and the experimenter pressed the corresponding response key (left or right arrow key). Visual and verbal feedback and encouragement were provided.

2.2.5.2 Practice phase.

Eight practice trials were presented in a fixed order. In the speed discrimination task, the comparison speeds were 3, 2.5, 2, 1.75, 1.5, 1.25, 1.2, and 1.1 times that of the reference speed. In the motion coherence task, the coherence levels of comparison stimuli were 90%, 80%, 70%, 60%, 50%, 40%, 30% and 20%. Participants received feedback as before, but there was no criterion for proceeding to the next phase.

2.2.5.3 Threshold estimation phase.

Speed discrimination and motion coherence thresholds were determined using the QUEST technique (Watson & Pelli, 1983; see Section 2.2.1). Two QUEST functions of 32 trials ran interleaved, varying temporal order (reference speed vs. comparison speed presented first). An additional 16 catch trials presented the comparison stimulus used in the criterion phase yielding 80 trials in total for each speed condition. Each QUEST had a beta value of 3.5 and a lapse rate set to 0.02. As recommended by Watson and Pelli (1983), a random jitter was added to values suggested by the QUEST, of up to plus or minus 0.5 deg/sec and 1.25 deg/sec for the slow and fast conditions of the speed discrimination task, respectively, and of up to plus or minus 5% coherence in the motion coherence task. No feedback was given regarding performance. A short break was given after a block of 20 trials in which the participant was shown a simulated graph of the “points” s/he and his/her “opponent” (“Astro” or the “camera system”) had attained. These points were fixed for all participants to minimise reward and motivation effects on threshold estimates.

The Space Cadet Training School is the best in the country. We have very high standards.

Lots of space cadets come to this training school, but it is very competitive. Only the best space cadets will be able to make it to space.

Astro is a space cadet just like you who really wants to go to space.

If you want to go to space, you need to make sure you get more points than him!

Figure 2.2 Screenshots presented in the introductory phase of the speed discrimination task.

The fireflies are kept in two viewing boxes: one with a red frame and one with a blue frame.

However, the zookeeper always forgets to shut a door of one of the boxes and the fireflies are getting lost!

InsectLand has put in a new camera system to watch the boxes. It tells the zoo when a door has been left open.

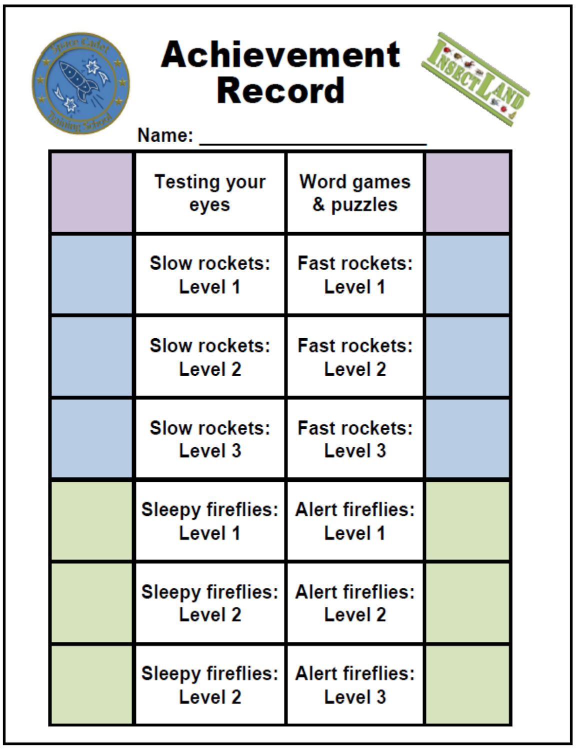
InsectLand wants to know whether their camera system is effective, or whether a person watching the fireflies could do better.

Can you beat the computer and save the fireflies?

Figure 2.3 Screenshots presented in the introductory phase of the motion coherence task.

2.2.6 General procedure

The procedure was approved by the Institute of Education's Faculty Research Ethics Committee. Parents gave their informed consent and children provided their verbal assent. Children were seen individually either at school or at home in three or four sessions each lasting approximately 30 minutes. The experimental tasks were presented in two separate sessions, with each session consisting of one condition of the speed discrimination task and one condition of the motion coherence task. The order of presentation of these conditions was counterbalanced between participants. The acuity test, WASI and ADOS-G were administered in further sessions.



Achievement Record

Name: ____________________

🟪	Testing your eyes	Word games & puzzles	🟪
🟦	Slow rockets: Level 1	Fast rockets: Level 1	🟦
🟦	Slow rockets: Level 2	Fast rockets: Level 2	🟦
🟦	Slow rockets: Level 3	Fast rockets: Level 3	🟦
🟩	Sleepy fireflies: Level 1	Alert fireflies: Level 1	🟩
🟩	Sleepy fireflies: Level 2	Alert fireflies: Level 2	🟩
🟩	Sleepy fireflies: Level 2	Alert fireflies: Level 3	🟩

Figure 2.4 Record card

"Slow rockets" and "Fast rockets" refer to the slow (1.5 deg/sec) and fast (6 deg/sec) conditions of the speed discrimination task, respectively, and "Sleepy fireflies" and "Alert fireflies" refer to the slow (1.5 deg/sec) and fast (6 deg/sec) conditions of the motion coherence task. "Word games and puzzles" relates to the Wechsler Abbreviated Scales of Intelligence (WASI; Wechsler, 1999).

For the experimental tasks, participants were tested binocularly in a dimly illuminated room with a viewing distance of 50 cm from the computer monitor maintained with a chin-rest. Participants were instructed to maintain central fixation throughout stimulus presentation. The experimenter continuously monitored participants' eye movements, providing regular reminders to maintain fixation and initiated trials only when the participant was attending. Children were given a 'Record of Achievement' with which they recorded their progress through the experimental sessions with stamps (Figure 2.4).

2.2.7 Data analysis

The proportion of incorrect responses for catch trials was calculated for each participant for each condition in both the speed discrimination and motion coherence tasks. Participants not performing significantly above chance in the catch trials of a given condition (i.e., responding incorrectly in 5 or more of the 16 catch trials) were deemed unable to do the task. Five children with autism and 6 TD participants were excluded from the motion coherence analysis on this basis.

For the remaining participants, the percentage of incorrect responses to catch trials was used as an estimate of lapse rate for fitting psychometric functions (Treutwein, 1995). For each participant, data for trials presented in the QUEST functions for each condition in each task were bootstrapped (Efron & Tibshirani, 1993), drawing *N* random samples (with replacement) from the data of a particular condition (where *N* is the number of trials). Using the estimated lapse rate[3], these sampled data were fit with a cumulative Gaussian function, using the 'maximum likelihood' fitting method described by Watson (1979) to obtain an estimate of the point at which a participant obtained 75% correct performance in log units. This procedure was repeated 100 times and the average threshold was calculated. Speed discrimination thresholds were converted to Weber fractions to allow comparability with previous studies by

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[3] Note that the same pattern of results was obtained when the lapse rate was fixed for all participants.

dividing the just noticeable difference threshold value by the reference speed (1.5 deg/sec or 6 deg/sec).

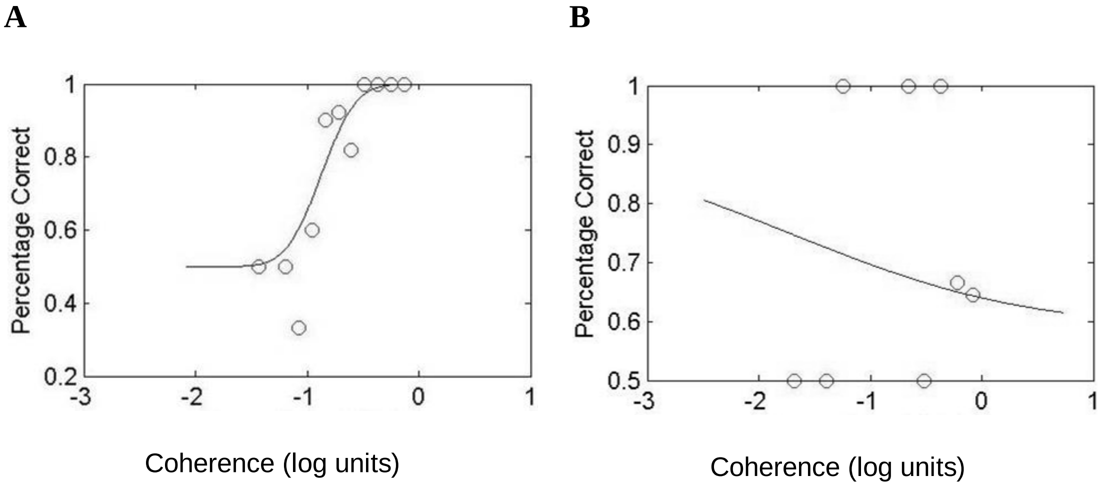

Figure 2.5 Examples of well-fitting and poorly fitting psychometric functions.

(A) Data from a typically developing (TD) participant in the slow (1.5 deg/sec) condition of the motion coherence task that were well-fit with a psychometric function. This participant was therefore retained in the dataset. (B) Data from a TD participant in the slow condition of the motion coherence task which yielded a poorly fitting psychometric function. This participant was removed from the dataset.

Upon inspection of psychometric curves, poorly fitting functions (e.g., those with flat slopes, or negative slope values; see Figure 2.5) were removed from the dataset. One TD child was removed from the motion coherence analysis due to a poorly fitting function in the slow condition, and 3 TD children were removed from the speed discrimination analysis due to poorly fitting functions in either the slow (*n* = 2) or fast (*n* = 1) conditions. Finally, the data were screened for potential outliers. *Z* scores were calculated using the mean threshold values and standard deviations (in log units) for each group in each condition. Outliers were identified as data-points with *z* scores of absolute values above 3. Screening revealed one outlying point in the fast condition of the motion coherence task belonging to a TD participant. Removing this outlier did not change the pattern of the analysis of variance (ANOVA) results and so this point was retained in the sample to increase statistical power but replaced with a threshold value corresponding to a *z* score of -2.5 (Tabachnick & Fidell, 2007). To minimise the effects of skewness and kurtosis, all analyses were conducted with log threshold values. However, for ease of interpretation, linear units are displayed in Figures 2.6 and 2.7.

2.3 Results

2.3.1 Speed discrimination thresholds

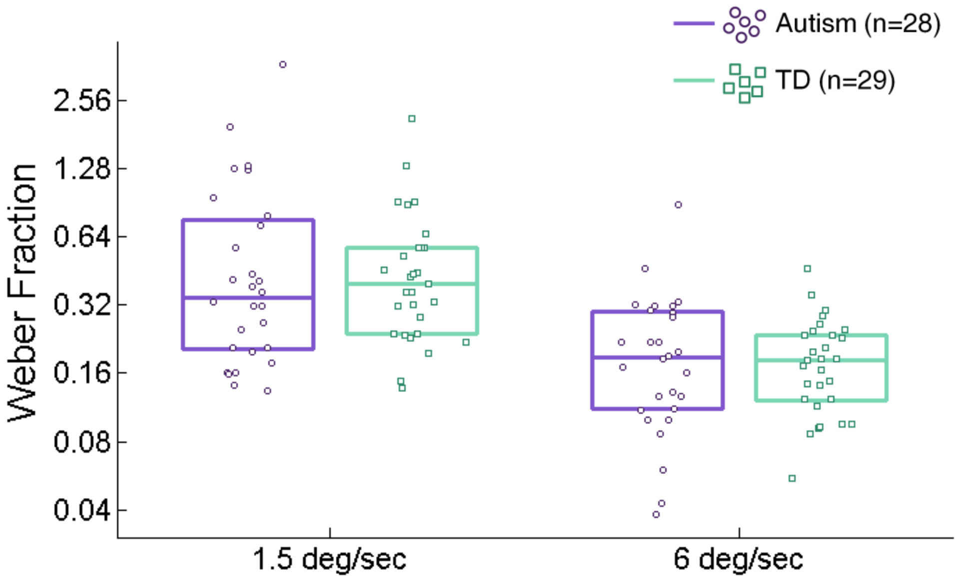

Figure 2.6 Speed discrimination thresholds
Individual Weber fractions for speed discrimination for children with autism (purple circles) and typically developing children (TD, green squares) in slow (1.5 deg/sec) and fast (6 deg/sec) reference speed conditions. Box plots represent median values and interquartile ranges for each group. N.b. Data are presented with outliers replaced (Tabachnick & Fidell, 2007). Statistical analyses were conducted on log Weber fractions.

Twenty-eight children with autism (three females) and 29 TD children (five females) were included in the speed discrimination analyses, following the data screening procedures described above (Section 2.2.7). The children with autism and TD children in this subset of participants were matched in terms of age, *t*(52.78) = .67, *p* = .50, VIQ, *t*(55) = 1.63, *p* = .11, PIQ, *t*(55) = 1.45, *p* = .15, and FSIQ, *t*(55) = 1.80, *p* = .08. Preliminary analysis revealed neither an effect of the order in which participants completed slow and fast conditions on Weber fractions, *F*(1, 53) = .85, *p* = .36, nor any interactions between order and group (autism, TD) or speed condition (1.5 deg/sec, 6 deg/sec), *p*s $\geq$ .11. This factor was therefore not included in further analysis.

Examination of Figure 2.6 suggests that both children with autism and TD participants were more sensitive to speed differences in the fast reference speed (6 deg/sec) condition than the slow reference speed (1.5 deg/sec) condition. A mixed-design ANOVA on log Weber fractions was conducted with group (autism, TD) as the between-participants factor and speed condition (1.5 and 6 deg/sec) as the within-participants factor. Age and FSIQ were entered as covariates due to known effects of age (C. Manning et al., 2012) and IQ (Koldewyn et al., 2010) on motion discrimination thresholds. However, the within-participants factor of speed was initially assessed in the absence of covariates (as within-participants effects can be masked when between-participants covariates are added; Delaney & Maxwell, 1981). Overall, higher thresholds were found in the slow condition (M = -.39, SD = .33) than the fast condition (M = -.77, SD = .26), $F(1, 55) = 84.10$, $p < .01$, $\eta_p^2 = .61$. Both covariates of age and FSIQ had significant effects on Weber fractions (age: $F(1, 53) = 7.47$, $p = .01$, $\eta_p^2 = .12$; FSIQ: $F(1, 53) = 10.48$, $p < .01$, $\eta_p^2 = .17$), and FSIQ interacted with speed condition, $F(1, 53) = .89$, $p = .01$, $\eta_p^2 = .13$. When controlling for age and FSIQ, there was no main effect of group, with the children with autism having a similar mean Weber fraction to the TD children (autism: M = -.61, SD = .22; TD: M = -.55, SD = .22), $F(1, 53) = .97$, $p = .33$. Furthermore, there was no significant interaction effect between speed condition and group, $F(1, 53) = .72$, $p = .40$.

2.3.2 Motion coherence thresholds

Twenty-three children with autism (three female) and 25 TD children (five female) were included in the motion coherence analyses, following the data screening procedures described in Section 2.2.7. The children with autism and TD children in this subset did not significantly differ in age, *t*(44.90) = .33, *p* = .75, or PIQ, *t*(46) = 1.57, *p* = .12. However, the children with autism had lower VIQ scores (*M* = 101.87, *SD* = 12.92) than the TD children (*M* = 109.44, *SD* = 11.04), *t*(46) = 2.19, *p* = .03. The children with autism also had lower FSIQ scores (*M* = 103.04, *SD* = 13.71) than the TD children (*M* = 110.84, *SD* = 11.36), *t*(46) = 2.15, *p* = .04. Initial ANOVA analysis confirmed that the order of speed conditions did not have a significant effect on motion coherence thresholds, *F*(1, 45) = .98, *p* = .33, and did not interact with group or speed condition (*p*s ≥ .09). This factor was therefore removed from further analysis.

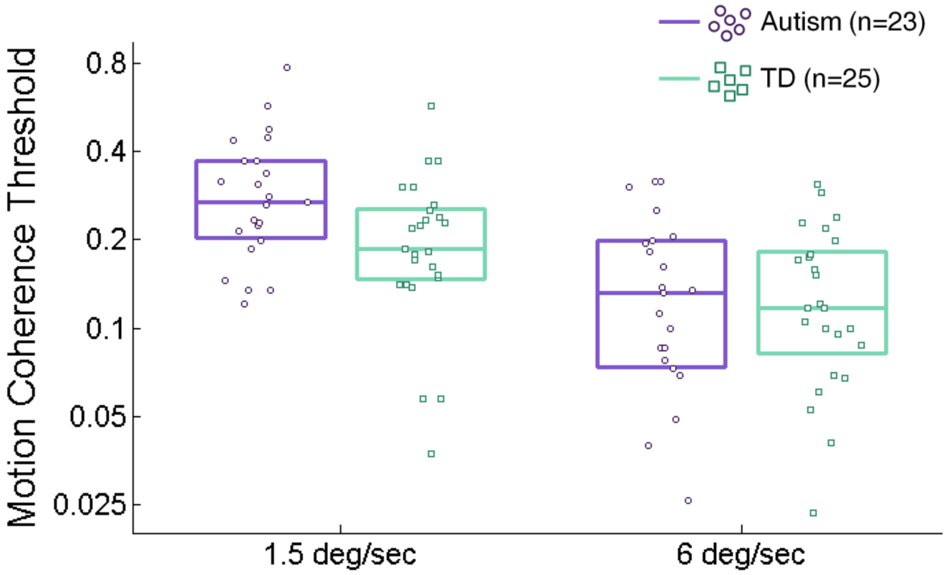

Figure 2.7 Motion coherence thresholds

The proportion of coherently moving dots required for coherent motion detection for children with autism (purple circles) and typically developing children (TD; green squares) in slow (1.5 deg/sec) and fast (6 deg/sec) speed conditions. Box plots represent median values and interquartile ranges for each group. N.b. Data are presented with outliers replaced (Tabachnick & Fidell, 2007). Statistical analyses were conducted on log thresholds.

The coherence thresholds presented in Figure 2.7 suggest that both children with autism and TD children were more sensitive to coherent motion in the fast (6 deg/sec) than the slow (1.5 deg/sec) condition. This was confirmed with an ANOVA on log motion coherence thresholds with group (autism, TD) as a between-participants factor, and speed condition (1.5 deg/sec, 6 deg/sec) as a within-participants factor. Children had higher motion coherence thresholds in the slow condition (*M* = -.65, *SD* = .25) than the fast condition (*M* = -.94, *SD* = .31), *F*(1, 46) = 32.76, *p* < .01, η_p^2 = .42. Next, age and FSIQ were added into the ANOVA model as covariates. While there was no main effect of either age, *F*(1, 44) < .01, *p* = .99, or FSIQ, *F*(1, 44) = 2.47, *p* = .12, there was an interaction between speed condition and age, *F*(1, 44) = 4.79, *p* = .03, η_p^2 = .10. Speed condition did not significantly interact with FSIQ, *F*(1, 44) = 3.00, *p* = .09.

There was no significant effect of group, with the children with autism having similar mean coherence thresholds (*M* = -.78, *SD* = .22) as the TD children (*M* = -.82, *SD* = .22), *F*(1, 44) = .43, *p* = .52. However, there was a significant interaction between speed condition and group on motion coherence thresholds, *F*(1, 44) = 7.08, *p* = .01, η_p^2 = .14. In order to determine the source of this interaction, one-way ANOVAs were conducted to determine the effect of group for slow and fast conditions separately, whilst covarying for age and FSIQ. The children with autism had significantly higher thresholds than the TD children in the slow condition (autism: *M* = -.56, *SD* = .21; TD: *M* = -.74, *SD* = .26), *F*(1, 44) = 5.74, *p* = .02, η_p^2 = .12, but there was no group difference in thresholds in the fast condition (autism: *M* = -.96, *SD* = .35; TD: *M* = -.93, *SD* = .27), *F*(1, 44) = 1.02, *p* = .32.

2.3.3 Identifying deviant scores

It has previously been suggested that, even when no overall group differences in performance are found, there may be a subgroup of individuals with autism who have elevated thresholds relative to the TD group (Milne et al., 2006). Therefore, *z* scores were constructed using the means and standard deviations of the TD group, and ‘deviant scores’ were identified as points lying more than 1.65 standard deviations away from the TD group mean (Milne et al., 2006; Ramus et al., 2003).

Table 2.2 Identifying extreme scores on threshold measures

Threshold measure	*Relative 'impairment'* $z > 1.65$ n	*Within typical range* $-1.65 \leq z \leq 1.65$ n	*Relative 'strength'* $z < -1.65$ n
Children with autism			
Speed discrimination (1.5 deg/sec)	5	21	2
Speed discrimination (6 deg/sec)	2	23	3
Motion coherence (1.5 deg/sec)	2	21	0
Motion coherence (6 deg/sec)	0	20	3
Typically developing children			
Speed discrimination (1.5 deg/sec)	2	26	1
Speed discrimination (6 deg/sec)	1	27	1
Motion coherence (1.5 deg/sec)	1	21	3
Motion coherence (6 deg/sec)	0	23	2

Note. Numbers of children with z scores more than 1.65 SD above the typically developing (TD) group mean (indicating relative 'impairment'), children within the typical range of the TD group, and children with z scores more than 1.65 SD below the TD group mean (indicating relative 'strength').

As shown in Table 2.2, there were children with autism who had elevated thresholds relative to the TD group in both the speed discrimination and motion coherence tasks. However, there were also children with autism who had *reduced* thresholds relative to the control mean (i.e., increased sensitivity), in all task conditions apart from the slow condition of the motion coherence task. Likewise, there were children in the TD group with relative 'impairments' and 'strengths' relative to the rest of the group. Interestingly, the children with extreme z scores were not always consistent across task conditions. Therefore, it does not seem to be the case that there are a subgroup of children with autism who perform particularly poorly in these tasks (c.f., Milne et al., 2006).

2.3.4 Cross-task correlations

Various animal and human adult studies and models have suggested that the processing of motion coherence and speed information may involve similar areas of the brain, and perhaps similar mechanisms (see Section 1.4.1). Therefore, cross-task correlations were investigated to assess whether the two abilities are associated during childhood (see Table 2.3). Due to the large number of correlations, a conservative significance level of $p < .01$ was adopted. Once controlling for the potentially confounding effects of age and FSIQ (Table 2.4), there was a marginally significant relationship between motion coherence performance in the slow condition and speed discrimination performance in the fast condition in the children with autism ($p = .01$). No other relationships between motion coherence performance and speed discrimination performance were found in children with autism (ps ≥ .02), and no cross-task correlations reached significance for TD children once controlling for age and FSIQ (all ps ≥ .18; see Table 2.4).

2.3.5 Relationships between thresholds and other variables

2.3.5.1 Relationships with age and ability.

As shown in Table 2.3, speed discrimination performance reduced with age in children with autism in the fast speed condition ($p < .01$) but not the slow condition ($p = .03$). Age was not related to speed discrimination performance in either speed condition for TD children (ps ≥ .07). Motion coherence thresholds were not related to age in either condition in either group (ps ≥ .08). PIQ and FSIQ scores were related to speed discrimination sensitivity in the slow condition in both children with autism and TD children (ps < .01), with higher scores being associated with lower thresholds. These relationships were not significant in the fast condition of the speed discrimination task (ps ≥ .05). VIQ scores were not related to speed discrimination performance in either group (ps ≥ .02). Motion coherence sensitivity was not related to any IQ measure in children with autism (ps ≥ .13) although motion coherence thresholds in the fast condition were related to VIQ scores in the TD group ($p < .01$), with higher verbal abilities being associated with lower thresholds.

Table 2.3 Bivariate correlations between thresholds and other variables

	Children with autism								*Typically developing children*							
	Speed discrimination				*Motion coherence*				*Speed discrimination*				*Motion coherence*			
	1.5 deg/sec		*6 deg/sec*		*1.5 deg/sec*		*6 deg/sec*		*1.5 deg/sec*		*6 deg/sec*		*1.5 deg/sec*		*6 deg/sec*	
Measure	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Speed discrimination																
1.5 deg/sec	-	-							-	-						
6 deg/sec	**.55**^{a}	**< .01**	-	-					.31^{b}	.10	-	-				
Motion coherence																
1.5 deg/sec	.38^{c}	.08	.44^{c}	.04	-	-			-.31^{c}	.15	-.32^{c}	.14	-	-		
6 deg/sec	.40^{c}	.06	.12^{c}	.58	.38^{c}	.08	-	-	.32^{c}	.14	.16^{c}	.47	.02^{d}	.93	-	-
Age	-.42^{a}	.03	**-.60**^{a}	**< .01**	-.02^{c}	.93	-.18^{c}	.41	-.34^{b}	.07	-.04^{b}	.82	.36^{d}	.08	-.34^{d}	.10
VIQ	-.43^{a}	.02	-.12^{a}	.53	-.14^{c}	.53	-.32^{c}	.13	-.24^{b}	.22	-.41^{b}	.03	-.10^{d}	.65	**-.53**^{d}	**< .01**
PIQ	**-.50**^{a}	**< .01**	-.10^{a}	.62	.23^{c}	.30	-.15^{c}	.51	**-.55**^{b}	**< .01**	-.21^{b}	.28	.11^{d}	.59	-.29^{d}	.17
FSIQ	**-.53**^{a}	**< .01**	-.12^{a}	.55	.05^{c}	.84	-.25^{c}	.25	**-.51**^{b}	**< .01**	-.37^{b}	.05	.01^{d}	.95	-.49^{d}	.01
SCQ	.16^{e}	.41	.10^{e}	.63	.05^{f}	.84	.37^{f}	.10	-.15^{e}	.47	-.18^{e}	.38	.22^{c}	.32	<.01^{c}	.99
ADOS-G																
Communication	-.42^{a}	.03	-.29^{a}	.13	-.19^{c}	.40	-.42^{c}	.05								
Social interaction	**-.56**^{a}	**< .01**	-.30^{a}	.12	-.25^{c}	.25	-.25^{c}	.25								
SB/RI	**-.49**^{a}	**< .01**	-.33^{a}	.09	.07^{c}	.74	-.20^{c}	.35								
DCDQ’07																
Control during movement	.05^{g}	.82	.02^{g}	.91	.17^{h}	.47	-.01^{h}	.98								
Fine motor control	.08^{g}	.71	.12^{g}	.57	.34^{h}	.13	-.03^{h}	.90								
General coordination	-.21^{g}	.30	.03^{g}	.90	.03^{h}	.92	-.30^{h}	.18								
Total score	-.07^{g}	.75	.05^{g}	.79	.19^{h}	.40	-.11^{h}	.63								

Note. Bivariate correlations between thresholds in speed discrimination and motion coherence tasks (slow: 1.5 deg/sec and fast: 6 deg/sec) and general developmental variables (age and IQ scores), levels of autistic symptomatology (Social Communication Questionnaire [SCQ; Rutter et al., 2003]; Autism Diagnostic Observation Schedule-Generic [ADOS-G; Lord et al., 1999]), and motor skills (Developmental Coordination Disorder Questionnaire [DCDQ’07; Wilson et al., 2007]). VIQ = Verbal IQ; PIQ = Performance IQ; FSIQ = Full-scale IQ; SB/RI = stereotyped behaviour/restricted interests. N.b. ADOS-G and DCDQ’07 data were not collected for TD children. A conservative significance level of $p < .01$ was adopted for all correlations. Significant correlations are highlighted in boldface.

^{a} $df = 26$, ^{b} $df = 27$, ^{c} $df = 21$, ^{d} $df = 23$, ^{e} $df = 25$, ^{f} $df = 20$, ^{g} $df = 24$, ^{h} $df = 19$.

Table 2.4 Partial correlations between thresholds and other variables

	Children with autism								*Typically developing children*							
	Speed discrimination				*Motion coherence*				*Speed discrimination*				*Motion coherence*			
	1.5 deg/sec		*6 deg/sec*		*1.5 deg/sec*		*6 deg/sec*		*1.5 deg/sec*		*6 deg/sec*		*1.5 deg/sec*		*6 deg/sec*	
Measure	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Speed discrimination																
1.5 deg/sec	-	-							-							
6 deg/sec	**.50**[a]	**< .01**	-	-					.17[b]	.39	-	-				
Motion coherence																
1.5 deg/sec	.49[c]	.02	.55[c]	.01	-	-			-.25[c]	.27	-.30[c]	.18	-	-		
6 deg/sec	.32[c]	.16	.04[c]	.87	.40[c]	.07	-	-	-.04[c]	.86	-.04[c]	.86	.16[d]	.46	-	-
SCQ	.13[e]	.54	.09[e]	.67	.07[f]	.79	.35[f]	.13	-.27[e]	.19	-.29[e]	.17	.09[c]	.69	-.07[c]	.76
ADOS-G																
Communication	-.47[a]	.02	-.29[a]	.16	-.19[c]	.41	-.41[c]	.06								
Social interaction	**-.68**[a]	**<.01**	-.32[a]	.11	-.25[c]	.27	-.26[c]	.26								
SB/RI	-.38[a]	.05	-.33[a]	.10	.07[c]	.75	-.11[c]	.65								
DCDQ'07																
Control during movement	-.05[g]	.81	-.15[g]	.49	.16[h]	.50	-.04[h]	.88								
Fine motor control	-.03[g]	.88	.11[g]	.62	.34[h]	.15	-.01[h]	.97								
General coordination	-.25[g]	.24	-.07[g]	.75	.02[h]	.94	-.31[h]	.20								
Total score	-.12[g]	.57	-.08[g]	.72	.19[h]	.44	-.13[h]	.61								

Note. Partial correlations between thresholds in the speed discrimination and motion coherence tasks (slow: 1.5 deg/sec and fast: 6 deg/sec), levels of autistic symptomatology (Social Communication Questionnaire [SCQ; Rutter et al., 2003]; Autism Diagnostic Observation Schedule-Generic [ADOS-G; Lord et al., 1999]), and motor skills (Developmental Coordination Disorder Questionnaire [DCDQ'07; Wilson et al., 2007]), once controlling for age and full-scale IQ. SB/RI = stereotyped behaviour/restricted interests. N.b. ADOS-G and DCDQ'07 data were not collected for TD children. A conservative significance level of $p < .01$ was adopted for all correlations. Significant correlations are highlighted in boldface.

[a] *df* = 24, [b] *df* = 25, [c] *df* = 19, [d] *df* = 21, [e] *df* = 23, [f] *df* = 19, [g] *df* = 22, [h] *df* = 17.

2.3.5.2 Relationships with motor skills.

To investigate the relationship between motion perception and motor coordination skills in children with autism, correlations between scores on the DCDQ'07 and performance in the psychophysical tasks were examined (Table 2.3). When controlling for developmental and individual differences in age and FSIQ, no significant relationships were found (*p*s ≥ .15; Table 2.4).

2.3.5.3 Relationships with autism symptoms.

Due to a proposed relationship between severity of autistic symptoms and sensory atypicalities (see Section 1.2), relationships between thresholds and scores on the SCQ and ADOS-G were investigated. Bivariate correlations are shown in Table 2.3. Once controlling for age and FSIQ, neither speed discrimination thresholds nor motion coherence thresholds were related to SCQ scores in either group (*p*s ≥ .13; Table 2.4). However, the speed discrimination thresholds of children with autism in the slow condition were related to scores in the reciprocal social interaction subscale of the ADOS (*p* < .01), where higher ADOS scores were related to lower speed discrimination thresholds (greater sensitivity to speed; see Table 2.4). All other correlations between speed discrimination thresholds and ADOS scores were non-significant (*p*s ≥ .02; Table 2.4). Motion coherence thresholds were not related to ADOS subscale or total scores once controlling for age and FSIQ (*p*s ≥ .06, Table 2.4).

2.4 Discussion

This study investigated the speed discrimination and motion coherence thresholds of children with autism aged 7 to 14 years and age- and ability-matched TD children for slow (1.5 deg/sec) and fast (6 deg/sec) speed conditions. Consistent with previous childhood studies of speed discrimination (Ahmed et al., 2005; C. Manning et al., 2012) and motion coherence (Ellemberg et al., 2004; Hadad et al., 2011; Narasimhan & Giaschi, 2012), thresholds varied with speed condition for all children, with greater sensitivities to fast (6 deg/sec) than slow (1.5 deg/sec) stimuli.

I was particularly interested, however, in sensitivity differences between children with autism and TD children, and how such group differences might vary between speed conditions. Unexpectedly, children with autism showed similar speed discrimination thresholds to TD children, both in the slow and fast reference speed conditions. Elevated motion coherence thresholds were found in children with autism, but only in the slow and not the fast condition.

Overall, these results suggest that speed discrimination is a dorsal stream function that is unimpaired in children with autism. This finding is contrary to accounts of impaired magnocellular/dorsal stream functioning in autism (Braddick et al., 2003; Greenaway et al., 2013) and Gepner's temporospatial processing disorders hypothesis (Gepner & Féron, 2009; Gepner et al., 2005, 2010), and suggests that children with autism were able to integrate information across space and time to perform the speed discrimination task effectively.

In the only previously published study investigating speed discrimination in autism, Chen et al. (2012) reported lower thresholds (i.e., heightened sensitivities) of adolescents with autism specifically when the ISI was prolonged to 3000 ms (and not when it was only 500 ms, as in the current study). Despite testing younger children, this study also found no group differences with an ISI of 500 ms. Chen et al. suggested that the enhanced performance of autistic adolescents in the long ISI condition reflected a local processing advantage in individuals with autism (Dakin & Frith, 2005; Mottron et al., 2006; see Section 1.6.2). Specifically, they proposed that the speed discrimination task was a dynamic equivalent of static tasks that have revealed a local processing advantage in individuals with autism, such as the Embedded Figures Test (Shah & Frith, 1983). Although it is clear how a local processing bias would lead to better performance in the latter task, it is less clear how a local processing strategy would necessarily confer an advantage in the speed discrimination task. In both the current study and that of Chen et al., the dots within each stimulus moved at the same speed with 100% coherence. The information provided at the global level is therefore consistent with that provided at the local level, and should not therefore interfere with speed discrimination. Chen et al.'s interpretation of increased local processing echoes Dakin and Frith's (2005) observation that tasks are often labelled 'local' when autistic individuals exhibit enhanced performance; a type of circularity which should be avoided.

According to Chen et al. (2012), the purported local processing advantage for speed discrimination is only apparent when a longer temporal window is available for processing. The stimuli presented in the current stimuli were of longer duration (1000 ms) than Chen et al.'s stimuli, leading to a total trial length of 2500 ms, compared to 1100 ms and 3600 ms in Chen et al.'s short and long ISI conditions, respectively. Presumably, longer stimulus presentations also serve to extend the temporal window for processing. It will therefore be important to both replicate Chen et al.'s findings and to probe the bounds of the temporal window required for individuals with autism to show enhancement in this task. Interestingly, it should be noted that a relationship was found between higher levels of autistic symptoms as measured by the ADOS-G and lower speed discrimination thresholds, and there were indeed a few children with autism who showed enhanced speed discrimination relative to the TD group. These results are therefore consistent with the view that some individuals with autism may be highly sensitive to speed differences, although overall children with autism perform similarly to TD children.

The results from the current study add to the complex pattern of results from previous studies investigating motion coherence perception in autism. Children with autism only had elevated motion coherence thresholds when the stimulus speed was slow (1.5 deg/sec), and not when the stimulus moved fast (6 deg/sec). The fact that children with autism had elevated thresholds specifically in the slow condition challenges the temporo-spatial processing disorders hypothesis (Gepner & Féron, 2009). Furthermore, as slow motion may be processed primarily by the parvocellular and ventral streams (Gegenfurtner, & Hawken, 1996; Hammett et al., 2005; Lorteije et al., 2008; Perrone, 2005), these findings are also inconsistent with magnocellular/dorsal stream accounts (Braddick et al., 2003; Greenaway et al., 2013). Reduced sensitivity specifically for slow speeds has also been reported in other developmental conditions, such as dyslexia (V. T. Edwards et al., 2004) and amblyopia (Hayward et al., 2011), further challenging the dorsal stream hypothesis.

The finding that motion coherence thresholds were elevated for slow speeds in children with autism is particularly interesting in the context of comparable sensitivities in the slow condition of the speed discrimination task, and speaks against a general problem with motion processing at slow speeds. A possible difference between the speed discrimination and motion coherence tasks is the extent of spatial integration required for good performance. While Chen et al. (2012) classified speed discrimination as a ‘local’ task and motion coherence as a ‘global’ task, it is unlikely that the speed discrimination task presented here could be considered local due to the relatively short lifetime (~83ms) of the stimulus dots. Furthermore, the involvement of higher motion areas such as MT/V5 in speed discrimination (e.g., Corbetta, Miezin, Dobmeyer, Shulman, & Peterson, 1991; Huk & Heeger, 2000; J. Liu & Newsome, 2005; Orban, Saunders, & Vandenbussche, 1995) appears to argue against the conceptualisation of speed discrimination as a purely ‘local’ task. It is possible, however, that individuals with autism integrate motion signals over a smaller spatial area or have a narrower focus of spatial attention than TD individuals (Ames & Fletcher-Watson, 2010; Lovaas, Schreibman, Koegel, & Rehm, 1971; Ronconi et al., 2012). This atypicality might selectively hinder performance in the motion coherence task, where signal dots are intermixed with noise dots, but not in the speed discrimination task, where each dot acts as a signal dot.

This suggestion is in line with the commonly-held assumption that elevated motion coherence thresholds arise from poor integration of local motion signals, in both typical development (e.g., Hadad et al., 2011) and in children with autism (e.g., Pellicano et al., 2005). Reduced integration of motion signals in children with autism could either directly reflect reduced global processing (e.g., Frith & Happé, 1994), or result from enhanced local processing (e.g., G. Davis & Plaisted-Grant, in press; Mottron et al., 2006). However, it is also possible that elevated motion coherence thresholds could arise from elevated levels of internal noise in autism (e.g., Rubenstein & Merzenich, 2003; Sanchez-Marin & Padilla-Medina, 2008; Simmons et al., 2009; but see also G. Davis & Plaisted-Grant, in press), leading to imprecision in estimating the directions of individual dots. In order to resolve these possibilities, Chapters 4 and 5 will aim to disentangle the local and global limits to motion processing in typical development and in children with autism, using an equivalent noise paradigm (Bex et al. in prep; Dakin et al., 2005; Tibber et al., 2014).

It remains a challenge to explain why children with autism showed elevated motion coherence thresholds only at the slow stimulus speed. There are at least four possible reasons for this result. First, models of motion perception have proposed two separate channels tuned to slow and fast speeds (e.g., Thompson et al., 2006) – channels that might be differentially affected by undersampling in autism. J. Liu and Newsome (2003) reported that there are fewer neurons tuned to slow speeds than neurons tuned to fast speeds in rhesus monkeys. If this is also true of the human brain, it is possible that undersampling in autism has a greater effect on the processing of slow motion than fast motion, due to naturally more sparse neuronal distributions. Chapter 5 will address this possibility using equivalent noise analysis.

Second, it is possible that the length of lifetime of dots had a disproportionate effect on motion coherence perception in the slow condition. Braddick, Lin, Atkinson, and Wattam-Bell (1998) reported that motion coherence thresholds were dependent on dot lifetime, with higher thresholds being obtained for stimuli with shorter lifetimes. The authors suggested that this might be attributable to the addition of noise, reduction of the temporal integration possible for each individual dot’s trajectory, and/or limiting tracking of individual dots. In this study, dot lifetime was kept constant at 5 frames for both speed conditions, meaning that dots were displaced a smaller spatial distance before their decay in the slow condition than in the fast condition. Indeed, Simmons et al. (2009) proposed that individuals with autism might be particularly susceptible to correspondence noise arising from false correspondences between dots on successive frames, which increases with shorter dot lifetimes. This possibility will be investigated further in Chapter 6.

Third, G. Davis and Plaisted-Grant (in press) suggested that elevated motion coherence thresholds may arise in individuals with autism due to enhanced processing of individual dot directions in conjunction with poor integration across dots, as a result of low neural noise (see Section 1.6.5). G. Davis and Plaisted-Grant further speculated that slow-moving stimuli are inherently less ‘noisy’ than fast-moving stimuli, leading to the possibility that motion coherence thresholds may be particularly elevated at slow speeds for individuals with autism, due to a lack of noise for efficient integration. However, the notion of one stimulus having more extrinsic noise than another stimulus is difficult to test, and stimulus noise is unlikely to affect perception unless the observer can consciously perceive the noise, as in the case of noise that has been added to the stimulus (e.g., Barlow, 1956; Dakin et al., 2005; Pelli, 1990).

Finally, atypical temporal integration may differentially affect the processing of slow and fast motion. C. E. Robertson et al. (2012) reported elevated motion coherence thresholds in adults with autism for fast-moving (5 deg/sec) stimuli only at short (200 ms) but not longer (400 ms and 1500 ms) durations. Perhaps children with autism require a longer optimal duration for extracting coherent motion information for slow-moving stimuli, leading to elevated thresholds in this study.

The current findings have important implications for studies addressing motion processing in autism. While previous studies have measured motion coherence thresholds in individuals with autism for mid-to-fast speeds (Table 1.1), the results of this study suggest that motion coherence thresholds may be particularly elevated for slow stimulus speeds. Narasimhan and Giaschi (2012) warned against generalising motion coherence deficits based on a specific combination of parameter values. Indeed, the results of this study and those of C. E. Robertson et al. (2012) and Ronconi et al. (2012) suggest that elevated motion coherence thresholds in autism may be found only at specific combinations of stimulus speed, duration and viewing conditions. Understanding the effects of stimulus parameters such as these will be important for resolving discrepancies between previous studies reporting motion coherence deficits in autism (e.g., Milne et al., 2002; Pellicano et al., 2005; Spencer et al., 2000), and those that do not (e.g., de Jonge et al., 2007; Del Viva et al., 2006; C. R. G. Jones et al., 2011).

Along with differences in stimulus parameters, it has also been suggested that differences in participant characteristics may underlie discrepant motion coherence results in autism (Simmons et al., 2009). Indeed, there was a considerable amount of between-participants variability in speed discrimination and motion coherence thresholds. However, in this study there was not a subset of autistic participants with consistently elevated discrimination thresholds (c.f., Milne et al., 2006) – rather, there were participants in both autism and TD groups who showed thresholds outside of the typical range. Individual differences in age and ability were controlled in the statistical analysis, but future research is needed to identify the other factors that may account for the large between-participants variability in both children with autism and TD children.

The current study enabled me to probe associations between speed discrimination and motion coherence abilities in both TD children and children with autism. Interestingly, in typical development there were no associations between speed discrimination and motion coherence sensitivities. In the children with autism, however, sensitivity to motion coherence in the slow condition was marginally related to speed discrimination performance in the fast condition. Conversely, sensitivity to motion coherence in the fast condition was unrelated to speed discrimination performance in either condition.

The lack of a relationship between speed discrimination and motion coherence perception in typical development may result from a lack of statistical power. Alternatively, it may indicate that different mechanisms are employed by the two tasks. It would therefore be interesting to see whether the predicted relationship would emerge when the tasks are more adequately matched in terms of integration demands (for example, by adding noise dots into the speed discrimination stimulus or by asking participants to compute the average speed of a stimulus containing multiple different speeds). Correlations between speed discrimination and motion coherence thresholds in the TD children may also have been weakened by different ages at which maturity is reached for the two tasks. To address this issue, a more developmental approach would need to be adopted, recruiting more children at each age to allow comparison of developmental trajectories for the two tasks (e.g., Annaz et al., 2010; Karmiloff-Smith, 2009). Understanding the interplay between motion coherence and speed discrimination through development will help inform adult models of motion processing, which have so far been successful in explaining direction detection, but less so in explaining speed perception (Burr & Thompson, 2011). If the two abilities follow different developmental trajectories, it may be important to consider developing distinct models for speed discrimination and coherent motion detection.

The possible relationship between motion coherence thresholds in the slow condition and speed discrimination thresholds in the fast condition for children with autism is intriguing. The nature of this relationship needs to be clarified with more developmental approaches, considering how the thresholds change with age in children with autism. Although the children with autism have comparable speed discrimination thresholds as TD children, it is possible that children with autism might be using alternative cognitive processes and brain networks in the service of speed discrimination compared to TD individuals (Karmiloff-Smith, 2009). Indeed, atypical trajectories of speed discrimination abilities in children with autism might explain why correlations are found between motion coherence thresholds and speed discrimination thresholds in children with autism, but not in TD children. Furthermore, the fact that speed discrimination performance in the fast condition is related to age in the children with autism, but not in the TD children may also indicate that the developmental trajectories underlying this performance differ between the groups. However, it is likely that the non-significant correlations between task performance and age in TD children result from low power, as previous studies have shown age-related changes in both speed discrimination and motion coherence in TD children (e.g., Hadad et al., 2011; C. Manning et al., 2012).

Previous studies have suggested that motion perception is linked to movement production in autism (Milne et al., 2006; Price et al., 2012). In contrast, in this study there was no relationship between performance in the motion processing tasks and motor difficulties, as reported in the DCDQ’07. However, whereas this study relied on parent-report, Milne et al. (2006) and Price et al. (2006) directly assessed movement skills by administering batteries of motor tasks to young people with autism. Hence, the current results do not necessarily preclude the possibility of a link between motor skills and motion perception in the sample, but suggest that the DCDQ’07 may not be sensitive enough to detect this relationship.

In sum, I have established that children with autism are equally sensitive to speed differences as TD children, both for slow and fast speeds. Children with autism showed elevated motion coherence thresholds only at a slow (1.5 deg/sec) and not a fast (6 deg/sec) stimulus speed. These results cannot be explained by current theoretical accounts such as the dorsal stream and temporospatial processing disorders hypotheses. Instead, the findings call for the development of more nuanced accounts of atypical motion processing in autism, which will be the focus of the remaining chapters. Chapters 3 to 5 will address two outstanding issues in particular. First, I will consider how performance in the psychophysical tasks reported here relates to subjective reports of the ‘world moving too fast’ (e.g., Grandin, 1995; D. Williams, 1999) and the ability to process speed-related information in everyday life (Chapter 3). Second, I will aim to elucidate the reasons for reduced motion coherence sensitivity in autism, particularly for slow speeds, using equivalent noise analysis (Chapters 4 and 5).

3 Parent-reported everyday speed perception in children with autism

3.1 Introduction

In Chapter 2, I reported that children with autism were just as sensitive to speed information as typically developing (TD) children in a psychophysical task and had elevated motion coherence thresholds only for slow-moving stimuli. Nevertheless, some adults with autism have reported feelings of the world "moving too fast" for them (Grandin, 1995; D. Williams, 1999), and it has been shown that individuals with autism perform better in some tasks (e.g., facial expression recognition and imitation [Tardif, Lainé, Rodriguez, & Gepner, 2007] and phoneme categorisation [Tardif, Thomas, Gepner, & Rey, 2002]) when stimuli are slowed down for them (see Gepner & Féron, 2009, for review). These results are not necessarily indicative of atypical sensitivity to speed information, but they may reflect atypical *subjective* experiences of fast-moving information. It is also possible that slowing stimuli down makes certain cues more salient for individuals with autism, allowing them to perform the tasks more easily. It is therefore important to understand the phenomenological experiences of speed-related information in autism and to consider how this may relate to performance in psychophysical tasks.

The aims of this study were twofold. First, I investigated whether parents report that their children with autism behave as if they process speed-related information atypically in everyday life, for example, by experiencing the world as if it is moving too fast. To address this question, a 16-item questionnaire was designed and given to the parents of children with autism and TD children who participated in

Chapter 2. Second, I considered whether individual differences in these sorts of everyday speed-related abilities (indexed by scores on the questionnaire measure) related to variation in performance on the psychophysical task. As noted in Chapter 2, there is considerable variability in the speed discrimination thresholds of children with autism and TD children. Thus, it is possible that those who experience more difficulties processing speed information in everyday life have higher speed discrimination thresholds in the psychophysical task. I also investigated relationships between everyday speed processing atypicalities and general developmental variables (age and ability) and other measures reported in Chapter 2, including motor coordination skills (as assessed by the Developmental Coordination Disorder Questionnaire 2007 [DCDQ'07; Wilson et al., 2007]) and autistic symptoms (as indexed by the Social Communication Questionnaire [SCQ; Rutter et al., 2003] and Autism Diagnostic Observation Schedule-Generic [ADOS-G; Lord et al., 1999]).

3.2 Methods

3.2.1 Participants

Questionnaires were distributed to all parents of children with autism and TD children who participated in the experimental tasks reported in Chapter 2 (see Section 2.2.2). Of all the parents of children in the final sample, questionnaires were returned by 26 parents of children with autism (three females) and 29 parents of TD children (four females). The groups of children did not differ in age (autism: *M* = 10 years; 3 months, *SD* = 1; 9; TD: *M* = 10 years; 5 months, *SD* = 2; 3), *t*(52.14) = .35, *p* = .72, or verbal IQ (VIQ; autism: *M* = 101.62, *SD* = 12.74; TD: *M* = 107.10, *SD* = 11.64), *t*(53) = 1.67, *p* = .10. However, the children with autism had significantly lower performance IQ (PIQ) scores (*M* = 101.69, *SD* = 13.61) than TD children (*M* = 109.38, *SD* = 13.87), *t*(53) = 2.07, *p* = .04, and there was also a significant group difference in full-scale IQ (FSIQ) scores (autism: *M* = 102.04, *SD* = 12.94; TD: *M* = 109.21, *SD* = 11.65), *t*(53) = 2.16, *p* = .04. Importantly, FSIQ was used as a covariate in the statistical analyses reported below, along with age.

3.2.2 Everyday speed perception questionnaire

To my knowledge, no existing questionnaires focus on the ability to process speed-related information. Therefore, a 16-item parent questionnaire was devised to assess children's speed perception in everyday life (see Table 3.1 for items). The items were chosen and refined through discussions between three researchers, and included those relating to the child's apparent difficulties in judging the speeds of moving objects (items 1 and 3) and tracking objects with their eyes (items 2 and 4), the child's perceived pleasurable (items 6, 8, 10 and 12) or aversive reactions (items 7, 9, 11 and 13) towards moving objects, the child's apparent difficulties in keeping up with the pace of everyday life and activities (items 5 and 14), as well as related difficulties in judging distances (item 15) and durations of time (item 16). Due to Gepner's suggestion that individuals with autism might have particular difficulties processing fast speeds (Gepner & Féron, 2009), many of the items asked parents to distinguish between fast- and slow-moving objects, with examples of both classes of objects (see items 1-4 and 6-13). As restricted and repetitive behaviours and stereotyped interests have been shown to be related to sensory atypicalities (Mandy, Charman, & Skuse, 2012), parents were asked to distinguish between reactions to repetitive and non-repetitive moving objects (items 6-13).

Table 3.1 Parent ratings for children with autism and typically developing (TD) children in the everyday speed perception questionnaire

Item	*Children with autism (n = 26)* *M (SD)* *Range*	*TD children (n = 29)* *M (SD)* *Range*
1. Does your child appear to have difficulties judging the speed of fast-moving things, such as moving cars and balls?	3.04 (1.34) 1 – 5	1.14 (0.44) 1 – 3
2. Does your child have difficulties following fast-moving things (such as cars) with their eyes?	2.62 (1.36) 1 – 5	1.03 (0.19) 1 – 2
3 Does your child appear to have difficulties judging the speed of slow-moving things, such as a person walking, or an aeroplane flying far in the distance?	2.50 (1.45) 1 – 5	1.03 (0.19) 1 – 2
4 Does your child have difficulties following slow-moving things (such as people walking) with their eyes?	1.96 (1.31) 1 – 5	1.03 (0.19) 1 – 2
5 Does your child appear to have difficulties with ‘keeping up’ with the pace of everyday life?	3.88 (1.21) 1 – 5	1.24 (0.51) 1 – 3
6 Does your child enjoy looking at fast-moving objects which might be repetitive, such as spinning tops, fans, or the wheels of a moving car?	3.16 (1.57) 1 – 5	2.41 (1.59) 1 – 5
7 Does your child find it distressing to look at fast-moving objects which might be repetitive, such as spinning tops, fans, or the wheels of a moving car?	1.46 (1.07) 1 – 5	1.10 (0.56) 1 – 4
8 Does your child enjoy looking at slow-moving objects which might be repetitive, such as the second-hand on a clock?	2.19 (1.41) 1 – 5	2.14 (1.36) 1 – 5
9 Does your child find it distressing to look at slow-moving objects which might be repetitive, such as the second hand on a clock?	1.50 (1.03) 1 – 5	1.10 (0.56) 1 – 4
10 Does your child enjoy looking at non-repetitive fast-moving objects, such as a ball being thrown or a car driving past?	2.38 (1.39) 1 – 5	2.55 (1.64) 1 – 5
11 Does your child find it distressing to look at non-repetitive fast-moving objects, such as a ball being thrown or a car driving past?	1.85 (1.22) 1 – 5	1.03 (0.19) 1 – 2
12 Does your child enjoy looking at non-repetitive slow-moving objects, such as raindrops on a window or snow falling?	2.42 (1.58) 1 – 5	2.59 (1.48) 1 – 5
13 Does your child find it distressing to look at non-repetitive slow-moving objects, such as raindrops on a window or snow falling?	1.31 (0.88) 1 – 5	1.03 (0.19) 1 – 2
14 Do you or teachers slow down or adjust the tempo of activities to make it easier for your child to engage in them?	3.81 (1.17) 2 – 5	1.41 (0.87) 1 – 4
15 Does your child have difficulties judging distances, such as judging how far away something is from him/her?	3.58 (1.39) 1 – 5	1.28 (0.59) 1 – 3
16 Does your child appear to have difficulties judging how much time has passed?	3.73 (1.54) 1 – 5	1.97 (0.98) 1 – 4
Total Score	41.38 (11.84) 18 – 61	24.10 (7.50) 16 – 39

Note. Each item was rated between 1 (*not at all like your child*) and 5 (*extremely like your child*). The minimum total score is 16 and the maximum total score is 80.

The rating scale was similar to that used in the DCDQ'07 (Wilson et al., 2007; see Section 2.2.3), which required parents to rate their child's abilities in relation to other children of the same age, on a scale from 1 (*not at all like your child*) to 5 (*extremely like your child*). The items yielded a total score between 16 and 80. Whereas higher scores on the DCDQ'07 reflect fewer motor coordination difficulties, higher scores on the speed questionnaire reflect *greater* difficulties in processing speed-related information. Parents were given the option of completing the survey either on paper, or online using SurveyMonkey software (www.surveymonkey.com).

3.3 Results

The mean, standard deviation and range of scores for each item for children with autism and TD children are presented in Table 3.1. Item scores were summed to create a total score for each participant, with a minimum score of 16 and a maximum score of 80. Overall, parents of children with autism reported significantly more atypicalities in processing speed-related information (*M* = 41.38, *SD* = 11.84) than parents of TD children (*M* = 24.10, *SD* = 7.50), *t*(41.43) = 6.38, *p* < .01, *r* = .50.

Table 3.2 Correlation matrix for questionnaire items

Item	*1.Judging fast*	*2.Tracking fast*	*3.Judging slow*	*4.Tracking slow*	*5.Keep up pace of life*	*6.Enjoy rep. fast*	*7.Distress rep. fast*	*8.Enjoy rep. slow*	*9.Distress rep. slow*	*10.Enjoy non-rep. fast*	*11.Distress non-rep. fast*	*12.Enjoy non-rep. slow*	*13.Distress non-rep. slow*	*14. Adjust tempo*	*15. Judging distances*
2.Tracking fast	.85 **	-													
3.Judging slow	.72 **	.85 **	-												
4.Tracking slow	.52 **	.68 **	.80 **	-											
5.Keep up pace of life	.72 **	.70 **	.60 **	.51 **	-										
6.Enjoy rep. fast	.21	.26 *	.34 **	.26 *	.33 **	-									
7.Distress rep. fast	.20	.31 *	.30 *	.43 **	.12	-.01	-								
8.Enjoy rep. slow	.14	.33 **	.30 *	.22	.11	.69 **	.20	-							
9.Distress rep. slow	.17	.30 *	.38 **	.43 **	.22 *	.20	.75 **	.22	-						
10.Enjoy non-rep. fast	-.14	-.02	.03	.03	-.07	.65 **	.23 *	.60 **	.18	-					
11.Distress non-rep. fast	.50 **	.60 **	.61 **	.74 **	.51 **	.25 *	.58 **	.16	.58 **	.05	-				
12.Enjoy non-rep. slow	-.09	.10	.12	.09	.03	.64 **	.22	.69 **	.16	.73 **	.19	-			
13.Distress non-rep. slow	.17	.38 **	.51 **	.69 **	.18	.15	.64 **	.29 *	.65 **	.13	.63 **	.09	-		
14.Adjust tempo	.73 **	.64 **	.54 **	.32 **	.78 **	.43 **	.05	.27 *	.15	.08	.32 **	.12	.08	-	
15.Judging distances	.81 **	.83 **	.76 **	.50 **	.76 **	.35 **	.20	.26 *	.26 *	.02	.52 **	.12	.24 *	.80 **	-
16. Judging time	.67 **	.53 **	.39 **	.31 *	.63 **	.27 *	.10	.14	.16	.01	.39 **	.06	<-.01	.64 **	.55 **

Note. * $p < .05$, ** $p < .01$. Abbreviations of items are presented here. For full items, see Table 3.1. $df = 53$.

3.3.1 Principal Components Analysis

No cases of singularity were identified in the item correlation matrix (defined as correlation coefficients > .9) and no items were completely uncorrelated with any other items (see Table 3.2). The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was good for all items together (KMO = .79; Hutcheson & Sofroniou, 1999; H. F. Kaiser, 1974), and the KMO statistics for all items were adequate (KMO > .5; Field, 2005; see Table 3.3). The questionnaire items were highly reliable (Cronbach's alpha = .89; Guttman's split-half coefficient = .92), although item 10 did not correlate well with the overall score ($r < .30$; Field, 2005; see Table 3.3) and was therefore removed from analysis. Reliability analysis confirmed that the remaining 15-item scale showed excellent reliability (Cronbach's alpha = .90; Guttman's split-half coefficient = .93). The final KMO statistic was .79, and Bartlett's test of sphericity was significant, $\chi^2(105) = 723.15$, $p < .01$, confirming the appropriateness of Principal Components Analysis (PCA) for these data.

PCA was conducted with the remaining 15 items. While it was predicted that parents of children with autism would report atypicalities to a greater extent, there was no *a priori* reason to predict that the factor structure underlying these abilities would differ between children with autism and TD children. All children were therefore included in the PCA analysis, which also had the effect of boosting statistical power. Direct oblimin rotation was applied due to a prediction that the extracted factors would be correlated, as all questionnaire items were designed to measure a common construct (atypicalities processing speed-related information).

Table 3.3 KMO statistics, item-total correlations and Cronbach's alpha if item deleted

Item	*KMO*	*Item-total correlation r*	*Alpha if item deleted α*
1. Difficulties judging speed of fast objects	.80	.67	.88
2. Difficulties tracking fast objects	.87	.78	.88
3. Difficulties judging speed of slow objects	.84	.75	.88
4. Difficulties tracking slow objects	.81	.64	.89
5. Difficulties with pace of everyday life	.88	.67	.88
6. Enjoy fast repetitive objects	.66	.57	.89
7. Distress at fast repetitive objects	.60	.37	.89
8. Enjoy slow repetitive objects	.71	.50	.89
9. Distress at slow repetitive objects	.68	.43	.89
10. Enjoy fast non-repetitive objects	.72	.27	.90
11. Distress at fast non-repetitive objects	.84	.64	.89
12. Enjoy slow non-repetitive objects	.64	.35	.90
13. Distress at slow non-repetitive objects	.77	.43	.89
14. Need to adjust tempo of activities	.86	.68	.88
15. Difficulties judging distances	.89	.77	.88
16. Difficulties judging time duration	.86	.54	.89

Note. KMO = Kaiser-Meyer-Olkin measure of sampling adequacy. All items have adequate KMO values (KMO >.5; Field, 2005). All items except item 10 correlate well with the overall score (*r* > .30; Field, 2005). For unabbreviated items, see Table 3.1.

Factors with eigenvalues above 1 were retained in the analysis (H. F. Kaiser, 1960), resulting in 3 factors (see Figure 3.1). This criterion was deemed appropriate as there were fewer than 30 variables and the average communality after extraction was greater than .7 (Field, 2005). The percentage of non-redundant residuals with absolute values over .05 was 41%, which is below the cut-off of 50% that would lead to concern for the assumptions of PCA (Field, 2005).

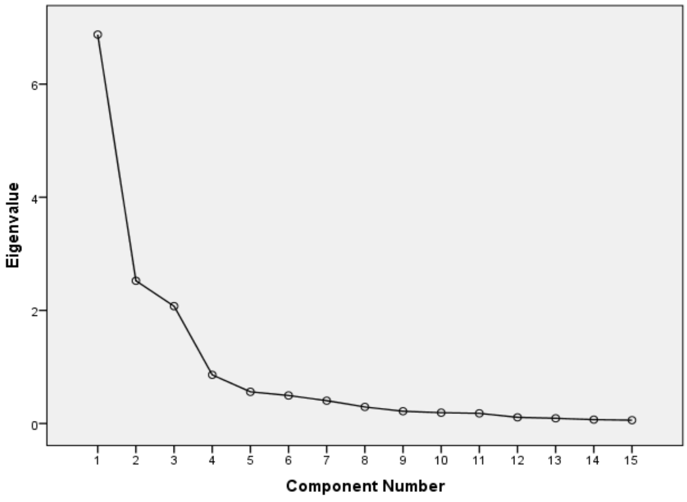

Figure 3.1 Scree plot showing eigenvalues of factors extracted from Principal Component Analysis

Table 3.4 Factor loadings

Item	*Factor 1: Difficulties Processing Speed-related Information*	*Factor 2: Distress Towards Moving Objects*	*Factor 3: Enjoyment Watching Moving Objects*
1.Difficulties judging speed of fast objects	**.94**	.04	-.14
2.Difficulties tracking fast objects	**.80**	.26	.02
3.Difficulties judging speed of slow objects	**.66**	.39	.05
4.Difficulties tracking slow objects	**.42**	**.64**	-.02
5.Difficulties with pace of everyday life	**.88**	.00	-.02
6.Enjoy fast repetitive objects	.22	-.08	**.84**
7.Distress at fast repetitive objects	-.12	**.87**	.01
8.Enjoy slow repetitive objects	.02	.09	**.87**
9.Distress at slow repetitive objects	-.05	**.82**	.08
11.Distress at fast non-repetitive objects	.36	**.69**	-.01
12.Enjoy slow non-repetitive objects	-.16	.05	**.91**
13.Distress at slow non-repetitive objects	-.07	**.91**	.03
14.Need to adjust tempo of activities	**.88**	-.19	.16
15.Difficulties judging distances	**.88**	.06	.07
16.Difficulties judging time duration	**.77**	-.13	.03
Rotation sums of squared loadings	6.05	4.32	2.82

Note: Factors were extracted through Principal Components Analysis with direct oblimin rotation. Items with loadings greater than .4 (J. P. Stevens, 1992) are highlighted in boldface.

The factor loadings from the pattern matrix are shown in Table 3.4, with items with factor loadings greater than .4 (J. P. Stevens, 1992) identified in boldface. Factor 1 explained 45.84% of the variance, and Factors 2 and 3 explained a further 16.83% and 13.83% of the variance, respectively. Therefore, the 3 factors together explained a large amount (76.50%) of the total variance. As shown in Table 3.4, 8 items had significant loadings (> .4; J. P. Stevens, 1992) onto Factor 1. These items shared a common theme of reflecting difficulties processing speed-related information, with the highest loading items being item 1 (difficulties judging the speed of fast objects), item 5 (keeping up with the pace of everyday life), item 14 (the need to adjust the tempo of activities) and item 15 (difficulties judging distances). Five items loaded highly onto Factor 2: item 4 (difficulties tracking slow objects), item 7 (distress at fast repetitive objects), item 9 (distress at slow repetitive objects), item 11 (distress at fast non-repetitive objects) and item 13 (distress at slow non-repetitive objects). Items 7, 9, 11 and 13 all share a common theme of distress towards moving objects. It is less clear how item 4 might be incorporated within this factor, although a possibility that could be tested in future research is that aversion to moving objects leads to poorer tracking ability. Three items loaded highly onto Factor 3, including item 6 (enjoying watching fast repetitive objects), item 8 (enjoying watching slow repetitive objects) and item 12 (enjoying watching slow non-repetitive objects). The three factors were thus labelled 'Difficulties Processing Speed-related Information', 'Distress Towards Moving Objects' and 'Enjoyment Watching Moving Objects'.

3.3.2 Group differences in factor scores

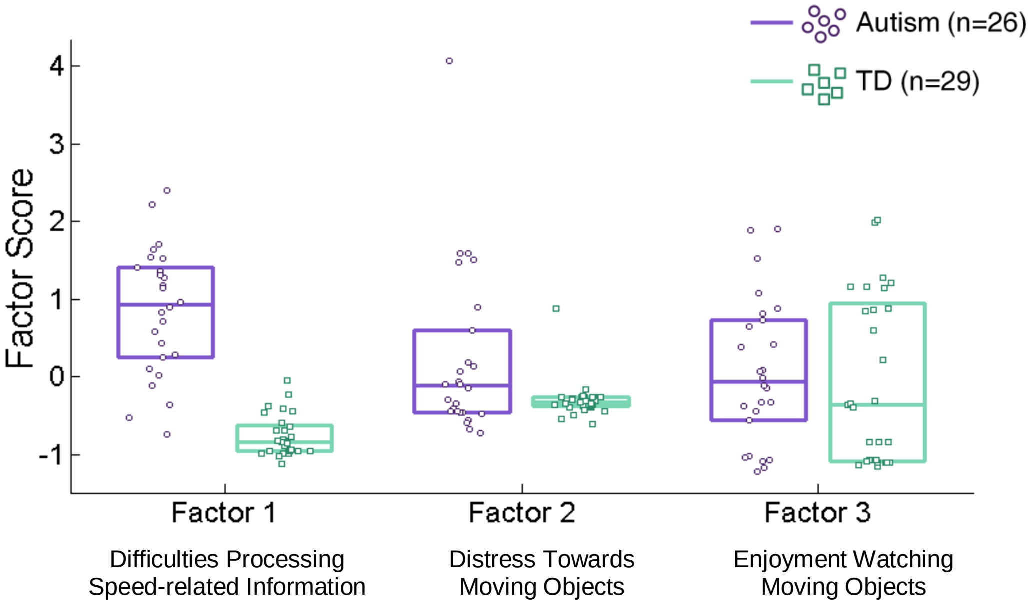

Figure 3.2 Factor scores identified through Principal Components Analysis on the everyday speed perception questionnaire.

Scores for children with autism are represented by purple circles and scores for typically developing (TD) children are represented by green squares. Box plots represent median scores and interquartile range for each group. N.b. Data are presented with outliers replaced (Tabachnick & Fidell, 2007).

Factor scores were calculated for each individual, as shown in Figure 3.2. Outliers were identified as scores lying over ±3 SDs from the group mean. Two outliers were identified in the 'Distress Towards Moving Objects' scores, with one in the autism group and one in the TD group. These outliers were replaced with scores corresponding to *z* scores of 2.5 (Tabachnick & Fidell, 2007; see also Section 2.2.7). Univariate analyses of variance (ANOVAs) were conducted on each factor score to compare children with autism and TD children whilst covarying for age and FSIQ. A corrected significance level of .017 was adopted to account for multiple comparisons.

Children with autism had significantly greater scores on Factor 1 (Difficulties Processing Speed-related Information; *M* = .85, *SD* = .82) than TD children (*M* = -.76, *SD* = .26), *F*(1, 51) = 86.25, *p* < .01, η_p^2 = .63, and neither covariate (age, FSIQ) had a significant effect on factor scores (*p*s ≥ .31). However, the groups did not differ in scores on Factor 2 (Distress Towards Moving Objects), *F*(1, 51) = 4.93, *p* = .03, η_p^2 = .09, or Factor 3 (Enjoyment Watching Moving Objects), *F*(1, 51) = .07, *p* = .80. The covariates had no significant effects on scores for Factor 2 or Factor 3, *p*s ≥ .15.

3.3.3 Relationship between factor scores and other variables

3.3.3.1 Relationships with age and ability.

Bivariate correlations between factor scores and age and ability are provided in Table 3.5. A conservative significance level of *p* < .01 was adopted to correct for multiple correlations. Factor scores were not related to age, in either the children with autism or TD children (*p*s ≥ .13). Additionally, no relationships were found between any IQ measure and factor score in either group (*p*s ≥ .21).

Table 3.5 Bivariate correlations between factor scores and other measures

	Children with autism						*Typically developing children*					
	Factor 1: Difficulties Processing Speed-related Information		*Factor 2: Distress Towards Moving Objects*		*Factor 3: Enjoyment Watching Moving Objects*		*Factor 1: Difficulties Processing Speed-related Information*		*Factor 2: Distress Towards Moving Objects*		*Factor 3: Enjoyment Watching Moving Objects*	
Measure	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Speed discrimination												
1.5 deg/sec	.34 [a]	.09	.24 [a]	.24	-.19 [a]	.35	<.01 [a]	.99	.36 [a]	.08	.05 [a]	.82
6 deg/sec	.14 [a]	.48	.22 [a]	.28	-.01 [a]	.96	-.27 [a]	.18	.33 [a]	.11	.14 [a]	.50
Motion coherence												
1.5 deg/sec	.12 [b]	.60	-.04 [b]	.85	.10 [b]	.66	.13 [c]	.57	-.03 [c]	.89	.36 [c]	.10
6 deg/sec	.48 [b]	.03	.26 [b]	.27	.07 [b]	.75	.30 [c]	.17	-.17 [c]	.46	.43 [c]	.05
Age	-.20 [a]	.32	-.31 [a]	.13	-.03 [a]	.89	-.06 [d]	.75	-.21 [d]	.27	-.01 [d]	.95
VIQ	-.14 [a]	.50	-.23 [a]	.25	-.02 [a]	.93	.01 [d]	.96	.21 [d]	.27	-.09 [d]	.64
PIQ	-.26 [a]	.21	-.18 [a]	.39	.18 [a]	.39	-.18 [d]	.36	-.16 [d]	.42	-.21 [d]	.28
FSIQ	-.20 [a]	.32	-.22 [a]	.29	.10 [a]	.64	-.11 [d]	.58	.01 [d]	.98	-.21 [d]	.28
SCQ	**.71 [e]**	**<.01**	.34 [e]	.10	.43 [e]	.03	.36 [f]	.06	-.11 [f]	.59	.34 [f]	.08
ADOS-G												
Communication	-.25 [a]	.22	-.21 [a]	.32	.19 [a]	.34						
Social interaction	-.30 [a]	.14	-.23 [a]	.25	.14 [a]	.50						
SB/RI	-.05 [a]	.82	-.21 [a]	.30	.14 [a]	.48						
DCDQ'07												
Control during movement	**-.54 [a]**	**<.01**	.12 [a]	.55	.06 [a]	.78						
Fine motor control	**-.66 [a]**	**<.01**	-.39 [a]	.05	-.32 [a]	.11						
General coordination	**-.57 [a]**	**<.01**	-.26 [a]	.20	-.13 [a]	.52						
Total score	**-.67 [a]**	**<.01**	-.12 [a]	.56	-.10 [a]	.64						

Note. Correlations between factor scores and thresholds in speed discrimination and motion coherence tasks (slow: 1.5 deg/sec, fast: 6 deg/sec), general developmental variables (age and IQ), measures of autism symptoms (Social Communication Questionnaire [SCQ; Rutter et al., 2003], Autism Diagnostic Observation Schedule-Generic [ADOS-G; Lord et al., 1999]) and motor skills (Developmental Coordination Disorder Questionnaire [DCDQ'07; Wilson et al., 2007]). VIQ = Verbal IQ; PIQ = Performance IQ; FSIQ = Full-scale IQ; SB/RI = stereotyped behaviour /restricted interests. N.b. ADOS-G and DCDQ'07 data were not collected for typically developing children. A conservative significance level of $p < .01$ was adopted for all correlations. Significant correlations are highlighted in boldface.

[a] *df* = 24, [b] *df* = 19, [c] *df* = 20, [d] *df* = 27, [e] *df* = 23, [f] *df* = 26.

Table 3.6 Partial correlations between factor scores and other measures

	Children with autism						*Typically developing children*					
	Factor 1: Difficulties Processing Speed-related Information		*Factor 2: Distress Towards Moving Objects*		*Factor 3: Enjoyment Watching Moving Objects*		*Factor 1: Difficulties Processing Speed-related Information*		*Factor 2: Distress Towards Moving Objects*		*Factor 3: Enjoyment Watching Moving Objects*	
Measure	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Speed discrimination												
1.5 deg/sec	.25 [a]	.24	.08 [a]	.72	-.20 [a]	.36	-.14 [a]	.52	.36 [a]	.08	-.14 [a]	.51
6 deg/sec	.04 [a]	.86	.05 [a]	.81	-.05 [a]	.83	-.37 [a]	.08	.37 [a]	.08	.04 [a]	.84
Motion coherence												
1.5 deg/sec	.13 [b]	.60	-.05 [b]	.84	.10 [b]	.68	.08 [c]	.75	.09 [c]	.72	.30 [c]	.21
6 deg/sec	.45 [b]	.05	.21 [b]	.39	.09 [b]	.72	.19 [c]	.43	-.29 [c]	.21	.22 [c]	.35
SCQ	**.71 [e]**	**<.01**	.33 [e]	.12	.44 [e]	.04	.35 [f]	.08	-.08 [f]	.69	.29 [f]	.15
ADOS-G												
Communication	-.24 [a]	.27	-.18 [a]	.40	.20 [a]	.35						
Social interaction	-.31 [a]	.15	-.24 [a]	.27	.15 [a]	.49						
SB/RI	.03 [a]	.90	-.14 [a]	.52	.13 [a]	.55						
DCDQ'07												
Control during movement	**-.62 [a]**	**<.01**	.06[a]	.79	.05 [a]	.81						
Fine motor control	**-.68 [a]**	**<.01**	-.41 [a]	.05	-.35 [a]	.10						
General coordination	**-.60 [a]**	**<.01**	-.30[a]	.16	-.16 [a]	.47						
Total score	**-.73[a]**	**<.01**	-.18 [a]	.41	-.11 [a]	.60						

Note. Correlations between factor scores and psychophysical thresholds in speed discrimination and motion coherence tasks (slow: 1.5 deg/sec, fast: 6 deg/sec), measures of autism symptoms (Social Communication Questionnaire [SCQ; Rutter et al., 2003] and Autism Diagnostic Observation Schedule-Generic [ADOS-G; Lord et al., 1999] scores) and motor skills (Developmental Coordination Disorder Questionnaire [DCDQ'07; Wilson et al., 2007] scores), once controlling for age and full-scale IQ. SB/RI = stereotyped behaviour/restricted interests. N.b. ADOS-G and DCDQ'07 data were not collected for typically developing (TD) children. A conservative significance level of $p < .01$ was adopted for all correlations.

[a] *df* = 22, [b] *df* = 17, [c] *df* = 18, [d] *df* = 25, [e] *df* = 21, [f] *df* = 24.

3.3.3.2 Relationships with psychophysical thresholds.

Table 3.5 presents bivariate correlations between factor scores and performance in the speed discrimination and motion coherence tasks reported in Chapter 2 for children with autism and TD children separately. Once controlling for age and intellectual ability (FSIQ), no relationships were found between psychophysical thresholds and factor score, in either group (*p*s ≥ .05, see Table 3.6).

3.3.3.3 Relationships with motor skills.

Next, I assessed whether factor scores were related to parent-reported motor difficulties in the DCDQ'07, as atypical processing of motion information could be related to atypical motor skills (Milne et al., 2006; Price et al., 2012). All subscales of the DCDQ'07 and the DCDQ'07 total score were negatively related to Factor 1 scores (Difficulties Processing Speed-related Information) in children with autism (*p*s < .01; see Table 3.5), which suggests that poorer motor skills (lower scores on the DCDQ'07) are related to greater difficulties in processing speed-related information (higher scores on corresponding items in the everyday speed perception questionnaire). These relationships remained significant even when controlling for age and FSIQ, *p*s < .01 (Table 3.6). Scores from Factor 2 (Distress Towards Moving Objects) and Factor 3 (Enjoyment Watching Moving Objects) were unrelated to DCDQ'07 scores (*p*s ≥ .05; Table 3.5 and Table 3.6).

3.3.3.4 Relationships with autism symptoms.

Interestingly, there was a positive relationship between Factor 1 scores (Difficulties Processing Speed-related Information) and SCQ scores for children with autism (Table 3.5), which remained significant and of strong magnitude once controlling for age and FSIQ, $r(21) = .71$, $p < .01$ (Table 3.6). This positive correlation suggests that parent-reported difficulties in processing speed-related information are related to the degree of retrospective autism symptoms. However, no relationships were found between current symptomatology, measured by the ADOS-G, and factor scores (ps $\geq .15$ once controlling for age and FSIQ; Table 3.6). Additionally, no relationships were found between factor scores and SCQ scores in the TD children (ps $\geq .08$ once controlling for age and FSIQ).

3.4 Discussion

A 16-item parent questionnaire was devised to assess children's abilities to process speed-related information in daily life. Fifteen highly reliable items were selected for PCA and three factors were identified: Difficulties Processing Speed-related Information, Distress Towards Moving Objects, and Enjoyment Watching Moving Objects. Consistent with self-reports from autistic adults (Grandin, 1995; D. Williams, 1999), the questionnaire results suggest that children with autism also process speed-related information atypically. The children with autism had significantly greater Difficulties Processing Speed-related Information than TD children, as reported by parents. Overall, the children with autism did not differ from the TD children in levels of Distress Towards Moving Objects or Enjoyment Watching Repetitive Movements, which may be due to a low frequency of reports of these atypicalities.

Gepner's temporospatial processing disorders hypothesis (Gepner & Feron, 2009) proposed that individuals with autism have particular difficulties in processing fast-moving objects whereas, in Chapter 2, I reported elevated motion coherence thresholds only for slow, and not fast, stimuli in children with autism. No clear distinction between slow and fast speeds emerged in the factor structure, with all three factors incorporating items relating to both slow- and fast-moving objects. Parents therefore do not appear to distinguish between atypicalities for processing slow and fast motion, which may be due, at least in part, to subjectivity as to what constitutes a slow or fast object. Moreover, the children themselves may distinguish between how they process slow- and fast-moving objects – a possibility that could be tested through a self-report version of the questionnaire, or through interviews, which have been used successfully to access the subjective sensory experiences of children with autism (Kirby et al., 2014; A. E. Robertson, 2012).

While parents of children with autism reported difficulties in processing motion information in everyday life, these were not related to psychophysical thresholds in either condition of the speed discrimination or motion coherence task (Chapter 2). Therefore, parent-reported atypicalities do not appear to relate well to speed discrimination and motion coherence thresholds measured experimentally. This discrepancy could arise as processing speed information in everyday situations is much more complex. In the experimental tasks, children were asked to compare just two stimuli, whereas in natural scenes, many more moving objects may be present, with complex distributions of directions and speeds (such as accelerating or decelerating objects). Furthermore, the difficulties reported by parents may involve interactions between perceptual and motor systems. For example, some parents reported that their children with autism had difficulties tracking moving objects with their eyes, which involves both perceptual and motor systems.

Interestingly, R. A. O. Davis et al. (2006) found that self-reported visual sensitivity atypicalities measured by an adapted version of the Structured Interview for Assessing Perceptual Anomalies (SIAPA; Bunney et al., 1999) were related to performance in psychophysical tasks (including a motion coherence task, see Table 1.1) in nine young people with autism aged 10 to 18 years. Perhaps this relationship between subjective experiences and psychophysical measures arose in R. A. O. Davis et al.'s study but not the current study because young people were able to give a more direct account of their sensory experiences than parents. However, the questionnaire given to parents in this study was designed to specifically target the processing of speed-related information in everyday life, rather than general sensory atypicalities. Future research may therefore assess whether performance in the tasks described in Chapter 2 relates to more general measures of sensory functioning (e.g., SIAPA, Bunney et al., 1999; Sensory Profile, Dunn, 1999).

In line with previous studies showing relationships between sensory atypicalities and autistic symptoms (e.g., Mandy, Charman, & Skuse, 2012), Difficulties Processing Speed-related Information were positively related to autistic symptoms measured by the SCQ. However, Difficulties Processing Speed-related Information were not related to autistic symptoms measured by the ADOS-G. This pattern of results may arise for two reasons. First, it is possible that Difficulties Processing Speed-related Information relate more strongly to restrospective autism symptoms than current symptomatology. Second, and perhaps more conceivably, the pattern of results could arise because the SCQ is a parent-report measure like the everyday speed perception questionnaire, whereas the ADOS-G is an observation tool. Indeed, previous reports have suggested poor agreement between parent-reported SCQ scores and ADOS-G scores (Bishop & Norbury, 2002). Additionally, the SCQ may be better at detecting low frequency autistic behaviours (such as sensory atypicalities and repetitive behaviours and restricted interests) than the

ADOS-G. The ADOS is an observation measure conducted over approximately 45 minutes, during which time it is unlikely to observe such low-frequency behaviours, and there is only one item measuring sensory behaviours.

Notably, scores on Factor 2 (Distress Towards Moving Objects) and Factor 3 (Enjoyment Watching Moving Objects) were not correlated with autism symptoms. However, theoretically, they seem to be examples of sensory hypersensitivity and sensory seeking, respectively (see Section 1.2). It therefore remains to be seen whether group differences in these factors might emerge within a larger sample, and whether these factor scores might relate to measures of atypical sensory functioning, such as the Sensory Profile (Dunn, 1999).

There was also a significant relationship between parent-reported motor skills on the DCDQ'07 and Difficulties Processing Speed-related Information. This relationship is consistent with the proposed link between sensory processing and motor skills (Milne et al., 2006; Price et al., 2012), and evidence of atypical motor responses to motion information in individuals with autism (Gepner & Mestre, 2002; Gepner et al., 1995; Greffou et al. 2012). Interestingly DCDQ'07 scores were not related to Distress Towards Moving Objects or Enjoyment Watching Moving Objects, suggesting that atypical motor skills are related to the *ability* to process speed-related information, rather than to emotional reactions to moving objects. The nature of the relationship between Difficulties Processing Speed-related Information and DCDQ'07 scores is unclear: atypical sensory perception might lead to atypical motor skills in children with autism and/or atypical movements might lead to atypical sensory input, which might in turn alter the development of sensory processing. Irrespectively, perception and action systems must be tightly coupled to enable children to interact within a dynamic world, for example when tracking objects with their eyes or catching a ball. Future research may therefore investigate this important link between perceptual and motor systems in individuals with autism.

In sum, the parent-report questionnaire proved to be highly reliable and enabled an initial examination into how children with autism process speed-related information in daily life. While requiring validation within a larger sample, these preliminary results suggest that children with autism have difficulties processing speed-related information in everyday settings and that these are related to motor difficulties. Given that parents of children with autism report atypicalities, it is perhaps surprising that more general difficulties are not observed in the psychophysical tasks (Chapter 2). While well-controlled psychophysical experiments are important in order to uncover the mechanisms behind atypical sensory functioning, it remains a challenge for future research to determine how performance in psychophysical tasks maps on to everyday functioning. Child self-report measures may in future allow more direct insights into the everyday processing of speed-related information in children with autism.

4 Local and global contributions to the development of coherent motion processing in typically developing children

4.1 Introduction

In Chapter 2, I reported that children with autism had elevated motion coherence thresholds specifically at slow (1.5 deg/sec) but not fast (6 deg/sec) stimulus speeds compared to age- and ability-matched typically developing (TD) children. Meanwhile, children with autism were just as sensitive to speed differences as TD children. I raised the possibility that children with autism might undersample local motion signals, which might not have a disruptive effect in a speed discrimination task where all dots are signal dots, but might be disadvantageous when signal dots are intermixed with noise dots. Indeed, elevated motion coherence thresholds are normally interpreted as evidence of reduced integration of motion signals in autism (e.g., Milne et al., 2002; Pellicano et al., 2005), which reflects notions of Weak Central Coherence (WCC; Frith & Happé, 1994; see Section 1.6.2). The effect of undersampling might be particularly pronounced for slow stimulus speeds, as there are fewer motion-sensitive neurons tuned to slow speeds than fast speeds (at least in the primate brain; J. Liu & Newsome, 2003).

However, motion coherence thresholds are not a pure measure of integration, and hence it is not necessarily true that elevated motion coherence thresholds indicate reduced sampling of motion information (Dakin & Frith, 2005). Indeed, elevated motion coherence thresholds in autism could also arise from imprecision in estimating individual dot directions – which could be the case if individuals with autism have higher levels of neural variability (or *internal noise*; Simmons et al., 2009) – and/or by a reduced ability to segment signal dots from masking noise dots (Dakin et al., 2005; Tibber et al., 2014; Webster, Dickinson, Battista, McKendrick, & Badcock, 2011). To test the account that individuals with autism undersample motion signals, it is necessary to employ a paradigm that can distinguish between the roles of local and global processing. The equivalent noise paradigm is based on comparing human performance to that of an ideal observer which is limited both by additive internal noise and by how completely it samples the information available from the stimulus (Pelli, 1990). When applied to direction integration (Dakin et al., 2005), *internal noise* maps onto the precision with which individual motion directions are estimated (i.e., local processing) and *sampling* represents an estimate of the effective number of local motion directions that are pooled (or averaged; i.e., global processing).

In Chapter 5, I investigate whether local processing and/or global processing limit motion coherence sensitivity in children with autism using the equivalent noise paradigm. Yet, understanding the typical development of global motion processing is critical for interpreting atypical motion processing in autism. The current chapter therefore seeks to understand what limits motion coherence sensitivity in typical development.

As reviewed in Section 1.4.2, sensitivity to coherent motion follows a protracted development in TD children, and only reaches adult-like levels by mid-to-late childhood (Gunn et al., 2002; Hadad et al., 2011). Also, coherent motion sensitivity may develop more gradually for slow stimuli than fast stimuli (Hayward et al., 2011), which echoes the development of speed discrimination abilities (C.

Manning et al., 2012). The gradual development of motion coherence sensitivity has been attributed to poor integration of local motion cues in young children (Hadad et al., 2011). Yet, as suggested above, it is also possible that this gradual development arises from increased internal noise in childhood, or difficulties segregating signal from noise.

This study used the equivalent noise paradigm (Barlow, 1956; Pelli, 1990) to determine whether local and/or global processing limits motion coherence sensitivity in development. Whereas motion coherence stimuli contain both signal dots and randomly moving noise dots, equivalent noise stimuli contain dots whose directions (on any one trial) are sampled from a single Gaussian distribution (Dakin et al., 2005). The standard deviation of this distribution is varied across conditions, in order to manipulate the level of stimulus variability (or 'external noise'; see Figure 4.1A). The observer is asked to discriminate the mean direction of dots and the performance measure is the smallest difference in direction from a fixed reference direction (e.g., upwards) that observers can reliably report. With no directional variance (i.e., when the standard deviation is 0 deg and all elements move in the same direction), the observer's performance is limited both by internal noise and sampling. Consequently, small amounts of extra external noise have little effect on thresholds, as it is swamped by the observer's own internal noise. However, as the level of external noise is increased, a point is reached where the external noise exceeds the internal noise inherent in the system, and thresholds start to increase with the addition of further external noise. An equivalent noise function can be fit to these data to derive estimates of the individual's internal noise and sampling (see Figure 4.1A).

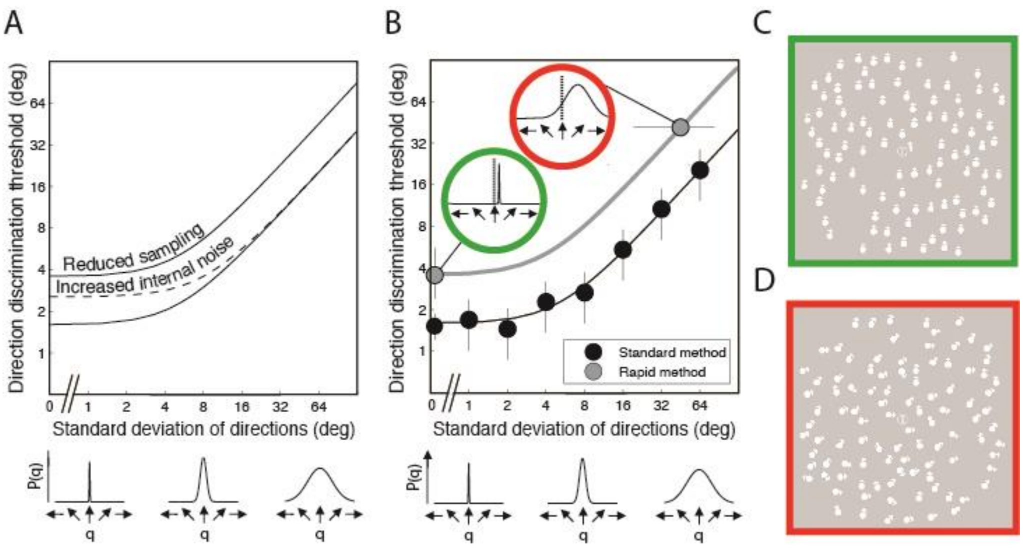

Figure 4.1 The equivalent noise model.

(A) Equivalent noise functions relating direction discrimination thresholds to the standard deviation of dot directions (i.e., external noise). Lower sampling is represented by an equivalent noise function that is shifted vertically upwards, whilst higher levels of internal noise require more external noise to be added before thresholds increase. (B) The black circles and curve represent the standard equivalent noise paradigm where direction discrimination thresholds are measured at multiple levels of external noise. Large standard deviations of dot directions reflect high external noise in the stimulus. The grey circles and curve are derived using a rapid version of the equivalent noise paradigm, which measures performance at two maximally informative noise levels. In the no-noise condition, there is no external noise (i.e., the standard deviation of dot directions is 0 deg) and the threshold is taken as the finest direction discrimination possible. In the high-noise condition, we measure the maximum noise that can be tolerated when the observer is judging if the pattern is moving ±45 deg of vertical. (C) Example of a stimulus in the no-noise condition, where the mean direction of dots is +4 deg, and the standard deviation of directions is 0 deg. (D) Example of a stimulus in the high-noise condition, where the mean direction of dots is +45 deg, and the standard deviation of dot directions is 45 deg. Arrows are provided for illustrative purposes only, to represent the direction of motion.

As thresholds are measured across a range of external noise levels, the equivalent noise method typically requires several thousand trials, making it unsuitable for investigating the visual abilities of children, who may get bored and become inattentive. However, a more efficient equivalent noise procedure has been developed, which provides reliable estimates of internal noise and sampling in fewer than 100 trials (Bex et al., in preparation; Tibber et al., 2014). In this novel method, two highly informative points on the equivalent noise function are probed (see grey line, Figure 4.1B). In one condition (‘*no-noise’*, Figure 4.1C), the standard deviation of dot directions is 0 deg, and an adaptive staircase procedure is used to estimate the finest direction discrimination possible. In the other condition (*'high-noise',* Figure 4.1D), an adaptive staircase procedure estimates how much directional variability can be tolerated while discriminating a large (±45 deg) directional offset. As these thresholds have confidence intervals that lie in orthogonal planes, the fit of the equivalent noise function is efficiently constrained to provide reliable estimates of internal noise and sampling.

Here, Tibber et al.'s (2014) rapid version of the equivalent noise direction integration paradigm was used alongside a traditional motion coherence task to investigate the factors limiting the development of global motion processing. These methods allowed me to investigate (1) how internal noise and sampling develop, and (2) the extent to which changes in these factors impact upon a commonly used measure of global motion processing, namely motion coherence thresholds. Due to the possibility of distinct developmental trajectories for different speeds (Hayward et al., 2011), equivalent noise and motion coherence tasks were presented at the same stimulus speeds as used in Chapter 2: slow (1.5 deg/sec) and fast (6 deg/sec).

It is commonly assumed that motion coherence thresholds are limited by poor integration of local motion information (e.g., Hadad et al., 2011). Therefore, my primary hypothesis was that sampling would increase with age and that this would contribute to age-related reductions in motion coherence thresholds. Deriving hypotheses about the development of internal noise was less straightforward. Internal noise has many potential sources, including photon noise, variability in the firing of action potentials, and variability in synaptic transmission (Faisal et al., 2008). Through development, neurons in area V1 undergo extensive synaptic pruning (Garey & de Courten, 1983; Huttenlocher & de Courten, 1987; Huttenlocher, de Courten, Garey, & Van der Loos, 1982), and the bandwidths of direction-selective cells reduce with age (at least in the primate brain; Hatta et al., 1998). It is possible that such developmental changes might manifest as reduced internal noise with age. Indeed, some researchers have noted that children have high trial-to-trial behavioural variability which decreases with age (e.g., B. R. Williams, Hultsch, Strauss, Hunter, & Tannock, 2005), where higher behavioural variability is thought to reflect higher neuronal variability (i.e., noise; M. D. Fox, Snyder, Vincent, & Raichle, 2007, but see also Beck, Ma, Pitkow, Latham, & Pouget, 2012). In line with this possibility, Skoczenski and Norcia (1998) have also reported that high levels of internal noise in infancy limit contrast sensitivity, and Buss et al. (2006) showed that increased levels of internal noise in children aged 5 to 10 years limited their performance in auditory detection and discrimination tasks compared to adults.

Alternatively, other researchers have suggested that neuronal variability in fact *increases* with age from 8 years to adulthood, as measured by trial-by-trial electroencephalogram (EEG) variability (McIntosh et al., 2008). The current study therefore aimed to investigate *how* internal noise and sampling change through childhood for a direction integration task and to determine whether such changes limit the development of coherent motion perception.

4.2 Methods

4.2.1 Participants

Five groups of participants were tested, including thirty 5-year-olds, twenty-eight 7-year-olds, twenty-seven 9-year-olds, twenty-one 11-year-olds and 31 adults. Children were recruited from schools in the South East of England and adults were recruited through the experimenter's contacts and through the Institute of Education and Birkbeck College, University of London. Normal or corrected-to-normal visual acuity was assessed with letter acuity tests using optical corrections where necessary. All children apart from two 7-year-olds, four 9-year-olds and three 11-year-olds were assessed using the Cambridge Crowding cards. The remaining children and adults were assessed with a Snellen acuity chart. Normal acuity was defined as a binocular acuity of 6/9 or better for 5- and 7-year-olds (because acuity is still maturing in this age range; Adams & Courage, 2002; Ellemberg, Lewis, Liu, & Maurer, 1999) and 6/6 or better for 9- and 11-year-olds and adults.

Nine 5-year-olds were excluded from the dataset, with one child failing to pass the visual acuity screening, one failing to reach criterion (see Section 4.2.3.1), three not performing significantly above chance in the catch trials (see Section 4.2.6.2) and four obtaining motion coherence thresholds above 100%, indicating an inability to perform the task. One 7-year-old could not complete the motion coherence task. Two 9-year-olds, one 11-year-old and one adult were excluded from the dataset due to diagnoses of developmental conditions. The final dataset therefore included twenty-one 5-year-olds (*M* = 5 years; 4 months, range 4;10 – 5;10, 14 females), twenty-seven 7-year-olds (*M* = 7 years; 3 months, range 6;7 – 7;10, 11 females), twenty-five 9-year-olds (*M* = 9 years; 2 months, range 8;8 – 9;9, 11 females), twenty 11-year-olds (*M* = 11 years; 3 months, range 10;8 – 11;9, 14 females) and 30 adults (*M* = 26 years; 9 months, range 21;5 – 35;10, 15 females).

4.2.2 Apparatus and stimuli

The stimuli were presented using MATLAB (The Mathworks Ltd.) using elements of the Psychophysics Toolbox software (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). Stimuli were displayed on a Dell Precision M4600 laptop at a frame rate of 60 Hz and a pixel resolution of 1366 x 768. This was in contrast to the previous study (Section 2.2.4) where stimuli were displayed on a CRT monitor. The initial choice to use a CRT monitor was based on the fact that these screens often have higher refresh rates and faster response times than LCD monitors. However, CRT monitors are not without limitations, as the nature of discontinuous illumination can lead to perceived flicker and imprecise stimulus timing (Y. Wang & Nikolić, 2011). Furthermore, CRT monitors are no longer produced commercially, and are heavy and cumbersome, making them difficult to transport to children's schools and homes. Stimuli were therefore presented on a LCD laptop screen in the current study, which facilitated the testing of more participants.

A yellow-bordered circular aperture (diameter = 15 deg) and anchor-shaped fixation point (0.57 deg x 0.57 deg) were presented against a grey background (see Figure 4.2). Two smaller yellow-bordered circular apertures (diameter = 6.12 deg) were presented to the left and right of the central aperture, serving as reference points for the reporting of motion direction. In the equivalent noise task, the left and right apertures were presented in the top corners of the screen and contained images of red and green reefs, respectively (see Figure 4.2A). In the motion coherence task, the left and right apertures were presented halfway down the screen, containing images of red and green rocks, respectively (see Figure 4.2B).

The stimuli were comprised of 100 randomly positioned white dots each with a diameter of 0.44 deg, yielding a dot density of 0.57 dots/deg^2. Dots drifted for 400 ms within the central aperture, with dot positions being updated every three frames with displacements of 0.075 deg and 0.3 deg in the slow (1.5 deg/sec) and fast (6 deg/sec) conditions, respectively. In contrast to the experiments presented in

Chapter 2, dots moved with unlimited lifetime. This change was made for two reasons: i) unlimited lifetime dots were used in the original equivalent noise direction integration task (Dakin et al., 2005), and ii) pilot studies revealed that adults had difficulties responding to catch trials correctly in the slow condition when limited lifetime stimuli were used.

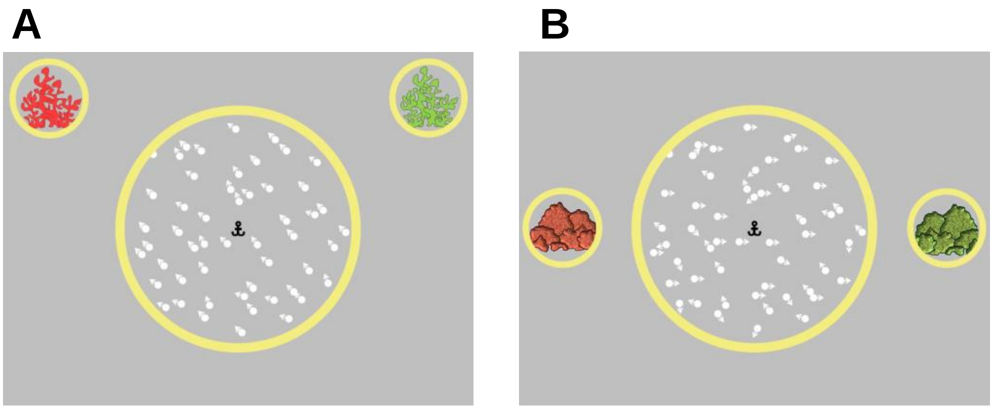

Figure 4.2 Schematic representation of stimuli

Representation of stimuli presented in the high-noise condition of the equivalent noise task **(A)** and the motion coherence task (**B**). The anchor-shaped fixation point, central yellow aperture and green (left) and red (right) “reefs” or “rocks” remained on the screen throughout the trial.

4.2.3 Procedure

Participants completed an equivalent noise task and a motion coherence task in each of two speed conditions: slow (1.5 deg/sec) and fast (6 deg/sec). In the equivalent noise task, dot directions were randomly sampled from a wrapped normal distribution with a specified mean and standard deviation. The equivalent noise task consisted of two interleaved conditions that probed two informative points on the equivalent noise function to constrain the fit of the model (see Figure 4.1B). In the no-noise condition, the standard deviation of dot directions was fixed at 0 deg (i.e., all dots moved in the same direction), while the mean direction of the dots was varied (leftward or rightward of vertical) to find the finest direction discrimination possible in the absence of stimulus noise. In the high-noise condition, the mean direction of dots was fixed at 45 deg leftwards or rightwards of vertical-upwards motion, and the standard deviation of dot directions was varied to find the maximum level of noise that could be tolerated whilst successfully identifying the signal direction 84% of the time (corresponding to the mean plus one standard deviation in a cumulative normal distribution).

The equivalent noise task was presented as “The Hungry Fish Game” (Figure 4.3). Participants judged whether a shoal of “fish” was “swimming” towards the red (left) or green (right) reef to find their food. Children were told that sometimes the fish all moved in the same direction (no-noise) and sometimes the fish moved in different directions (high-noise), in which case they had to determine the overall (i.e., average) direction. To aid motivation, children were told that they were competing against a cartoon character, “Scuba Sam”.

In the motion coherence task, a proportion of dots moved coherently in a single direction (90 deg leftward or rightward of vertical) while the remaining dots moved in random directions[4]. The task was presented within the context of “The Shark Attack Game” (Figure 4.4). Participants were asked to judge whether the shoal of “fish” was “swimming” towards the red (left) or green (right) rocks to hide from the “shark”. Children were told that the “fish” sometimes “panicked” when they saw the “shark”, causing them to go in different directions. To enhance motivation, children were told that they were competing against the “shark”.

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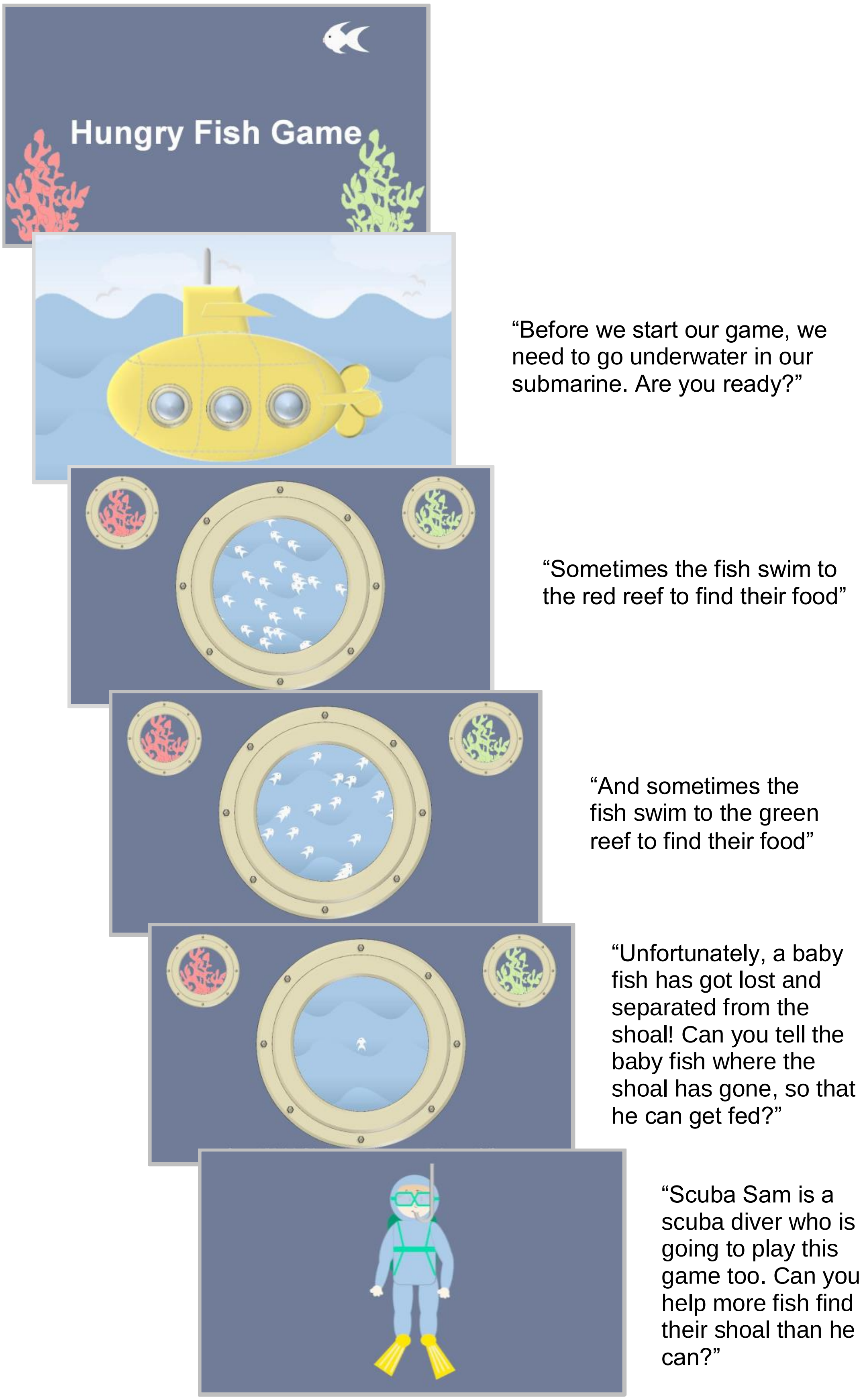
[4] Note that the motion coherence task presented in Chapter 2 differed considerably from the one presented here. In the former task, children had to judge which of two successive stimuli contained coherent motion. In the task described here, participants were presented with a single stimulus and were asked to discriminate the direction of coherent motion.



“Before we start our game, we need to go underwater in our submarine. Are you ready?”

“Sometimes the fish swim to the red reef to find their food”

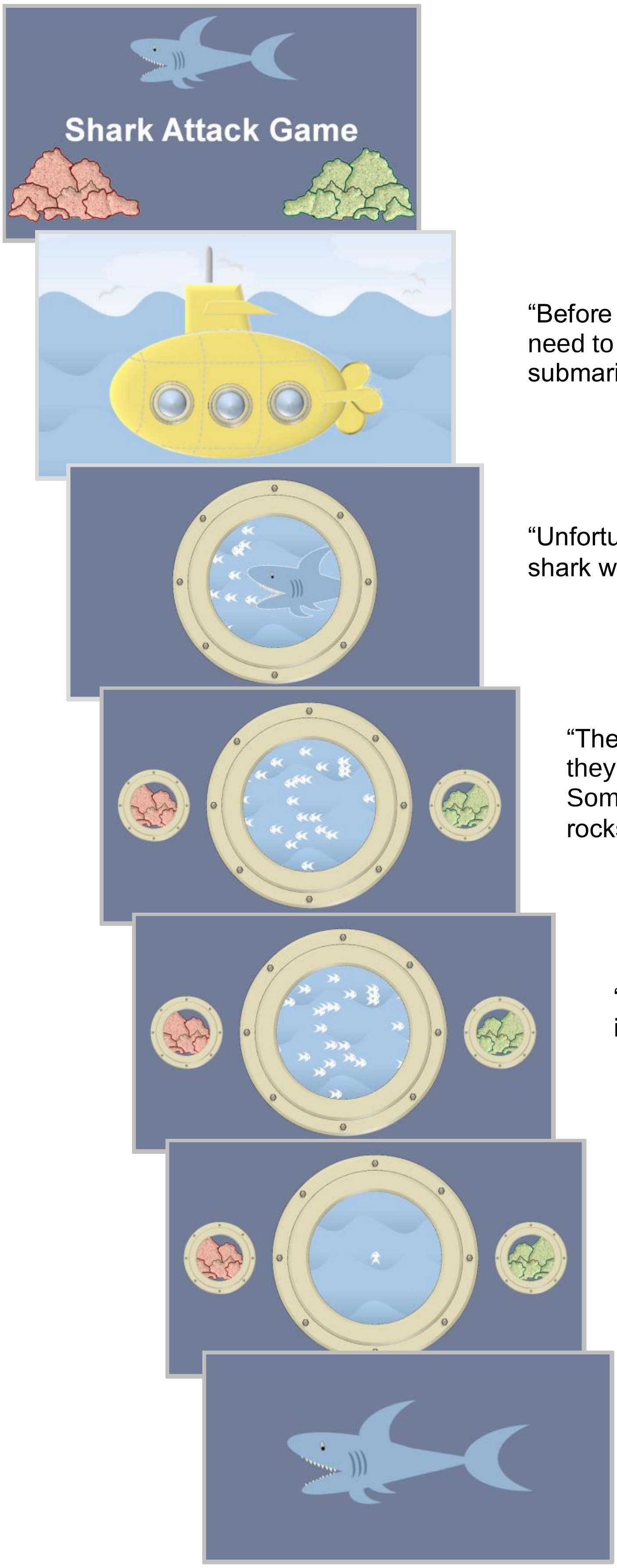
“And sometimes the fish swim to the green reef to find their food”

“Unfortunately, a baby fish has got lost and separated from the shoal! Can you tell the baby fish where the shoal has gone, so that he can get fed?”

“Scuba Sam is a scuba diver who is going to play this game too. Can you help more fish find their shoal than he can?”

Figure 4.3 Screenshots presented in introductory phase of equivalent noise task

The right column shows the text presented on the screen and read aloud by the experimenter.



“Before we start our game, we need to go underwater in our submarine. Are you ready?”

“Unfortunately there is a big shark who tries to get the fish!”

“The fish have two places where they hide from the shark. Sometimes they hide in the red rocks.”

“And sometimes they hide in the green rocks”

“Unfortunately, the baby fish has got lost and separated from the shoal. Can you tell the baby fish where the shoal is hiding, before the shark gets him?”

“You are going to be playing against the shark. Try to save as many fish as you can so he cannot get them!”

Figure 4.4 Screenshots presented in introductory phase of motion coherence task

The right column shows the text presented on the screen and read aloud by the experimenter.

Each equivalent noise and motion coherence task consisted of three levels: a combined demonstration and criterion phase (“level 1”), a practice phase (“level 2”), and a threshold estimation phase (“level 3”). In all levels in both tasks, direction (leftward or rightward of vertical) was randomised on each trial.

4.2.3.1 Demonstration and criterion phase.

Each task began with an introductory phase to explain the context of the “game” to participants (Figure 4.3 and Figure 4.4). Next, four demonstration trials were presented, two of which were designed to be “easy”, and two of which were “slightly harder”. In the equivalent noise task, the first two trials demonstrated the no-noise condition, whereby all the “fish” swam in the same direction. The first trial was “easy” (mean direction: ±45 deg) and the second trial was “slightly harder” (mean direction: ±15 deg). The next two trials demonstrated the high-noise condition, whereby some of the “fish” moved in slightly different directions. The first of these trials was designed to be “easy” (mean direction: ±45 deg, standard deviation: 15 deg) and the second “more difficult” (mean direction: ±45 deg, standard deviation: 35 deg). In the motion coherence task, the first two trials presented 100% coherent motion and the third and fourth trials presented 50% and 30% coherent motion, respectively.

Next, participants were presented with up to 20 criterion trials. In the equivalent noise task, no-noise stimuli were presented with a direction of 45 deg leftward or rightward of vertical. In the motion coherence task, dots moved with 100% coherence 90 deg leftward or rightward of vertical. Participants who failed to reach a criterion of four consecutive correct responses within 20 trials were given a short version of the task and excluded from analysis (*n* = 1, see Section 4.2.1).

Children responded either verbally or by pointing, with the experimenter relaying the response to the computer using the left and right arrow keys. Visual and verbal feedback and encouragement were provided.

4.2.3.2 Practice phase.

Eight practice trials were presented in a fixed order for each task with increasing difficulty. In the equivalent noise task, four no-noise stimuli with mean directions of ±35, 25, 15 and 5 deg were interleaved with four high-noise stimuli with standard deviations of 15, 30, 45 and 60 deg. In the motion coherence task, eight levels of coherence were presented: 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%. Participants received feedback as before, but there was no criterion for proceeding to the next phase.

4.2.3.3 Threshold estimation phase.

Both the equivalent noise and motion coherence tasks employed the QUEST adaptive staircase method (Watson & Pelli, 1983). QUEST functions had a beta value of 3.5 and a lapse rate set to 0.01, and tracked the 84% correct level for direction discrimination. In Chapter 2, QUEST was used to suggest test intensities and then a psychometric curve was fit to all of the data points in order to obtain the threshold for each participant (see Section 2.2.1). Here, however, thresholds were taken as the mean of QUEST's posterior probability density function and used to constrain the fit of the equivalent noise function following Bex et al. (in prep) and Tibber et al. (2014) (see Figure 4.1B). Therefore, no jitter was added to the values suggested by QUEST in this study, in order to estimate the thresholds as efficiently as possible (Kingdom & Prins, 2010).

In the equivalent noise task, two staircases (75 trials each) were interleaved for the no-noise and high-noise conditions. In the no-noise condition, the QUEST function tracked the basic direction offset threshold in the absence of noise. In the high-noise condition, the mean direction of motion was set to ±45 deg and QUEST tracked the maximum level of noise that could be tolerated whilst discriminating the mean direction. An additional 15 catch trials were interleaved randomly, presenting stimuli identical to those used in the criterion phase. This yielded 165 trials in total for each speed condition.

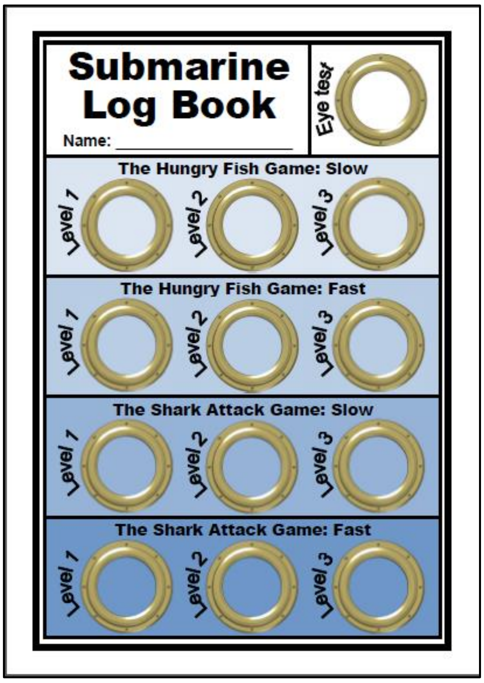
In the motion coherence task, a single QUEST staircase of 75 trials tracked the minimum coherence level required for accurate (84% correct) direction discrimination. As in the equivalent noise task, there were an additional 15 catch trials, which presented stimuli used in the criterion phase. This resulted in 90 trials in total for each speed condition. Trials were divided into four blocks of equal length for each condition of each task. When the end of a block was reached, participants were shown a simulated graph of the "points" they and their "opponent" ("Scuba Sam" or the "shark") had attained. These points were randomly jittered around a fixed set of values to minimise reward and motivation effects on threshold estimates.

4.2.4 Eyetracking

To establish whether developmental differences in task performance could be accounted for by differences in ability to maintain fixation, a Tobii X2-30 Compact eyetracker was mounted onto the screen to collect fixation data for a subset of participants, including twelve 5-year-olds (nine females), seventeen 7-year-olds (seven females), eleven 9-year-olds (six females), nine 11-year-olds (six females) and 10 adults (five females). A five-point calibration procedure was conducted before the introductory phase and fixation data were sampled at a rate of 40 Hz during stimulus presentation in the threshold estimation phase.

4.2.5 General procedure

The procedure was approved by the Institute of Education's Faculty Research Ethics Committee. All adult participants and parents of child participants gave their informed consent. Children provided verbal assent. Participants were seen individually for two sessions lasting approximately 25 minutes, each consisting of one equivalent noise and one motion coherence task. The order of presentation of conditions was counterbalanced across participants. Participants were seated in a dimly lit room 51 cm from the monitor which they viewed binocularly using a chin-rest. They were instructed to maintain central fixation throughout stimulus presentation, which the experimenter monitored, providing reminders to maintain fixation and only initiating trials when the participant was attending. Participants were each given a 'Submarine Log Book' with which they recorded their progress through the experimental sessions (see Figure 4.5).



Submarine Log Book
Name: ________________
Eye test

The Hungry Fish Game: Slow
Level 1 Level 2 Level 3

The Hungry Fish Game: Fast
Level 1 Level 2 Level 3

The Shark Attack Game: Slow
Level 1 Level 2 Level 3

The Shark Attack Game: Fast
Level 1 Level 2 Level 3

Figure 4.5 Submarine Log Book

Record card used by children to mark their progress throughout the testing sessions.

4.2.6 Data analysis

4.2.6.1 Equivalent noise analysis.

The equivalent noise model describes changes in direction discrimination threshold as a function of external noise:

$$\sigma^2_{obs} = [\sigma^2_{int} + \sigma^2_{ext}] \,/\, n_{samp} \qquad (1)$$

where σ^2_{obs} is the observer's threshold, σ^2_{int} is additive internal noise, σ^2_{ext} is the external noise added to the stimulus, and n_{samp} is the effective number of samples used to calculate the mean direction of the stimulus. This approach exploits additivity of variance, whereby internal noise and external noise contribute independently to an observer's direction discrimination threshold.

The equivalent noise task yielded two thresholds: a) the finest direction discrimination possible with no stimulus noise (no-noise threshold), and b) the maximum level of noise that could be tolerated (MTN) whilst discriminating a large signal offset of ±45 deg (in the high-noise condition). By running Monte Carlo simulations of a model observer's performance across a range of internal noise and sampling levels, Bex et al. (in prep.) have shown that – assuming that a participant's internal noise is negligible at high noise levels – sampling (n_{samp}) can be estimated from a linear transformation of their MTN threshold:

$$n_{samp} = \exp(0.0001 * MTN^2 + 0.0357 * MTN - 1.8093) \qquad (2)$$

As performance at low levels of external noise is determined both by internal noise and sampling, it is possible to use the estimate of n_{samp} to compute the level of internal noise, by rearranging equation (1). Thus, when external noise is zero ($\sigma^2_{ext} = 0$):

$$\sigma^2_{int} = \sigma^2_{obs} \times n_{samp} \qquad (3)$$

This approach assumes that observers do not change their sampling (or more generally, their strategy) as a function of external noise level. Consistent with this view, the equivalent noise function has been shown to fit direction discrimination data over a wide range of external noise levels (directional variability), under varying stimulus conditions (Dakin et al., 2005). Note that this approach does not assume that observers are necessarily averaging dot directions in the same way the model does to make perceptual judgements. No matter how observers perform the task the model will return the number of dots the observer is *effectively* averaging to make their judgements. Thus all noise and sampling estimates quoted are necessarily effective values since the observer's underlying strategy for performing the task cannot be known.

4.2.6.2 Data screening and transformation.

A lapse rate was calculated as the proportion of incorrect responses to catch trials for each participant for each condition for each task. A binomial test revealed that participants responding incorrectly on 4 or more of the catch trials were not performing significantly above chance. Three 5-year-olds were therefore excluded from analyses (see Section 4.2.1).

Analysis of variance (ANOVA) showed that lapse rates differed significantly across age groups, $F(4, 118) = 9.26$, $p < .01$, $\eta_p^2 = .24$ (5-year-olds: $M = .04$, $SD = .06$; 7-year-olds: $M = .02$; $SD = .04$, 9-year-olds: $M = .01$, $SD = .03$; 11-year-olds: $M = .01$, $SD = .03$; Adults: $M < .01$, $SD =.01$). *Post-hoc* Dunnett *t*-tests comparing each of the age groups with the adult groups revealed that 5-year-olds and 7-year-olds had significantly higher lapse rates than adults (*p*s < .01), whereas the 9- and 11-year-olds did not differ from the adult group (*p*s ≥ .36). There was no main effect of task, $F(1, 118) = .57$, $p = .45$, although higher lapse rates were found for the slow speed conditions ($M = .03$, $SD = .05$) than the fast speed conditions ($M = .01$, $SD = .03$), $F(1, 118) = 15.40$, $p < .01$, $\eta_p^2 = .12$. No interactions were significant (*p*s ≥ .06).

To ensure that any age-related and/or speed-related differences in threshold measures were not a by-product of differences in attention, an ideal observer model was run assuming different levels of lapse rate. Monte Carlo simulations allowed the effect of differing lapse rates on thresholds to be modelled. The lapse rate was averaged across tasks to yield an average lapse rate for each observer in each speed condition. The thresholds for each observer were then corrected according to their lapse rate for each speed condition, based on the simulation results.

Next, the no-noise threshold, MTN, internal noise, sampling and motion coherence threshold estimates in each speed condition were assessed for skewness and kurtosis. All measures showed significant skew (*p*s < .05) and the majority showed significant kurtosis (*p*s < .05). Consequently, all data were log-transformed. The data were then screened for outliers lying more than ±3SD from the mean for each age group in each speed condition. Two outliers were identified in the no-noise threshold values, which belonged to one adult in the slow condition and one 5-year-old in the fast condition. Five outliers were identified in the MTN values, including two 5-year-olds and one 7-year-old in the slow condition, and one 11-year-old and one adult in the fast condition. These outliers were retained in the sample to increase statistical power but the outlying scores were replaced with threshold values corresponding to a *z* score of ±2.5 (Tabachnick & Fidell, 2007; see also Section 2.2.7). No outliers were found in motion coherence thresholds, internal noise or sampling estimates. All of the analyses reported below were conducted with log-transformed, lapse-corrected values. Linear units are displayed in all figures for ease of interpretation.

4.2.6.3 Fixation analysis.

Raw fixation data were (*x*,*y*) coordinates sampled during stimulus presentation in each trial of the threshold estimation phase for left and right eye positions relative to the screen's active display area. The data were initially filtered according to a validity code from 0 (signifying the eye was definitely found) to 4 (signifying the eye was not found). All samples with validity codes of 2 or higher were discarded (Tobii Technology, 2013). The (*x*,*y*) coordinates were then averaged across the left and right eye for analysis. A measure of fixation stability was derived by pooling the standard deviations of fixation locations in *x* and *y* dimensions. The standard deviations were then log-transformed to minimise the effects of skewness and kurtosis and screened for outliers. No outliers (defined as data points lying more than ±3SD from the group mean) were found.

4.3 Results

4.3.1 Age-related changes in no-noise thresholds

Preliminary analysis revealed neither an effect of the order in which participants completed slow and fast conditions on no-noise thresholds, $F(1, 113) = .09$, $p = .77$, nor any interactions with age group or speed condition, $ps \geq .21$. This factor was therefore not included in further analysis.

No-noise thresholds reduced with age, with 5-year-olds having mean thresholds of 13.49 and 9.55 deg in the slow and fast conditions, respectively, which reduced to 5.50 and 3.55 deg in the adult group. To characterise the rate of developmental changes in no-noise thresholds, log threshold values were plotted as a function of log age and fit with a straight line (Figure 4.6A). The developmental trajectories for slow and fast speeds were then compared using the ANCOVA method outlined by Thomas et al. (2009). In this method, within-participants effects are initially examined using an ANOVA before assessing age-related changes by adding a covariate (as within-participants effects are masked when a between-participants covariate is added; Delaney & Maxwell, 1981; Thomas et al., 2009). An initial ANOVA with speed condition (slow, fast) as a within-participants factor revealed that significantly higher thresholds were found in the slow (*M* = .90, *SD* = .24) than the fast condition (*M* = .73, *SD* = .25), *F*(1, 122) = 69.26, *p* < .01, η_p^2 = .36. Next, an ANCOVA was conducted by adding log age into the model as a covariate. Overall, thresholds reduced significantly with age, *F*(1, 121) = 65.35, *p* < .01, η_p^2 = .35. There was no significant interaction between log age and speed condition, *F*(1, 121) = 1.17, *p* = .28, indicating a similar rate of development in the slow and fast conditions.

Dunnett *t*-tests (corrected for multiple comparisons) were conducted to determine when adult-like sensitivity was reached for slow and fast speed conditions. In the slow condition, 5-, 7- and 9-year-olds had significantly higher thresholds than adults (*p*s < .02), whereas 11-year-olds had adult-like thresholds (*p* = .13) (5-year-olds: *M* = 1.13, *SD* = .24; 7-year-olds: *M* = .89, *SD* = .22; 9-year-olds: *M* = .95, *SD* = .20; 11-year-olds: *M* = .86, *SD* = .21; adults: *M* = .74, *SD* = .15). Similarly, in the fast condition, 5-, 7- and 9-year-olds had significantly higher thresholds than adults (*p*s < .02) whereas the 11-year-olds did not (*p* = .18) (5-year-olds: *M* = .98, *SD* = .23; 7-year-olds: *M* = .78, *SD* = .24; 9-year-olds: *M* = .72, *SD* = .20; 11-year-olds: *M* = .66; *SD* = .16; adults: *M* = .55, *SD* = .21).

4.3.2 Age-related changes in maximum tolerable noise (MTN)

Next, I investigated age-related changes in MTN. The order in which slow and fast conditions were completed did not have an effect on MTN values, *F*(1, 113) = .61, *p* = .44, and did not interact with age group or speed condition (*p*s ≥ .28). This factor was therefore not analysed further.

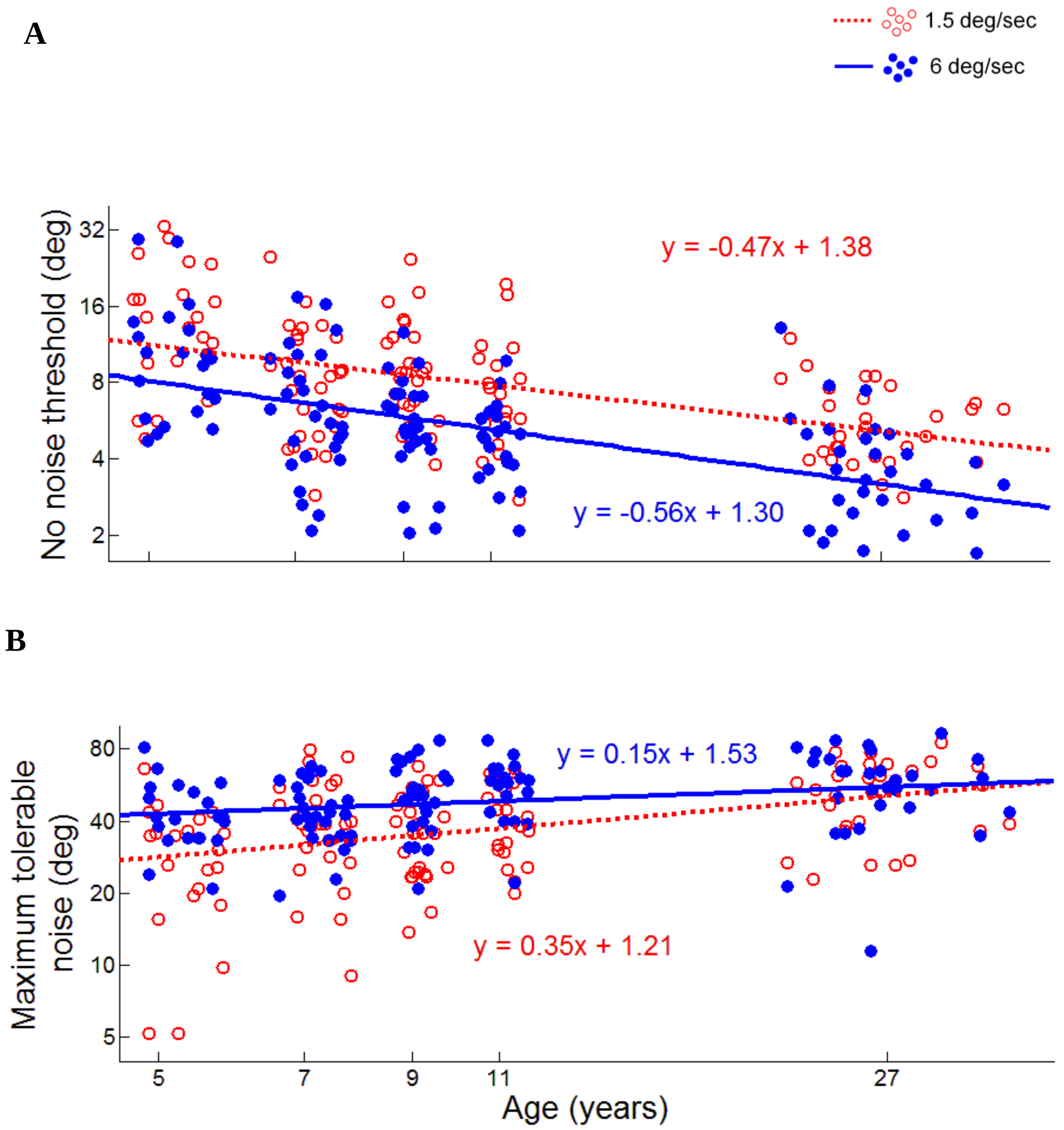


Figure 4.6 No-noise direction discrimination thresholds and maximum level of tolerable noise

Individual no noise-direction discrimination thresholds (A) and maximum level of tolerable noise (B) for slow (1.5 deg/sec; open red circles) and fast (6 deg/sec; filled blue circles) conditions as a function of age. Red dashed and blue solid lines represent the line of best fit for the slow and fast conditions, respectively, and equations are given in log units.

As shown in Figure 4.6, participants were able to tolerate more directional noise as they got older, with MTN increasing from 25.12 deg at age 5 to 50.12 deg in adults in the slow condition, and from 41.69 to 53.70 deg in the fast condition. The ANOVA and ANCOVA analyses were repeated using log MTN as the dependent variable. More noise could be tolerated in the fast condition (*M* = 1.68; *SD* = .16) than in the slow condition (*M* = 1.57; *SD* = .22), *F*(1, 122) = 36.21, $p < .01$, $\eta_p^2 = .23$. When log age was added into the model as a covariate, it was found that MTN increased across development, *F*(1, 121) = 21.12, $p < .01$, $\eta_p^2 = .15$. Furthermore, there was an interaction between speed condition and log age, *F*(1, 121) = 6.86, $p = .01$, $\eta_p^2 = .05$, suggesting a steeper rate of development in the slow condition.

Dunnett *t*-tests showed that 5-year-olds (*M* = 1.40, *SD* = .29) and 9-year-olds (*M* = 1.53, *SD* = .18) had significantly lower MTN values than adults (*M* = 1.70, *SD* = .16) in the slow condition (*p*s < .02) whereas 7-year-olds (*M* = 1.57, *SD* = .22) and 11-year-olds (*M* = 1.59, *SD* = .16) were not significantly different from adults (*p*s ≥ .07). In the fast condition, 5-year-olds had marginally higher MTN values (*M* = 1.62, *SD* = .14) than adults (*M* = 1.73; *SD* = .19; *p* = .05), and 7-year-olds (*M* = 1.62, *SD* = .13) had significantly higher MTN values than adults (*p* = .04). In contrast, 9-year-olds and 11-year-olds could tolerate similar levels of noise as adults (*p*s ≥ .81) (9-year-olds: *M* = 1.69, *SD* = .15; 11-year-olds: *M* = 1.73, *SD* = .13).

4.3.3 Age-related changes in internal noise

I then investigated the results from the equivalent noise analysis. Preliminary analysis confirmed that the order of conditions did not have a significant effect on internal noise estimates, *F*(1, 113) = .11, *p* = .74, and no interactions with group and speed condition (*p*s ≥ .83). Levels of internal noise reduced with age, with 5-year-olds having mean levels of 9.62 and 9.69 deg in the slow and fast conditions, respectively, which reduced to 6.72 and 4.80 deg in the adult group. Figure 4.7A presents log internal noise values plotted as a function of log age and fit with a straight line. An initial ANOVA with speed condition (slow, fast) as a within-participants factor revealed that significantly higher levels of internal noise were found in the slow (*M* = .87, *SD* = .24) than the fast condition (*M* = .79, *SD* = .25), *F*(1, 122) = 12.24, $p < .01$, $\eta_p^2 = .09$.

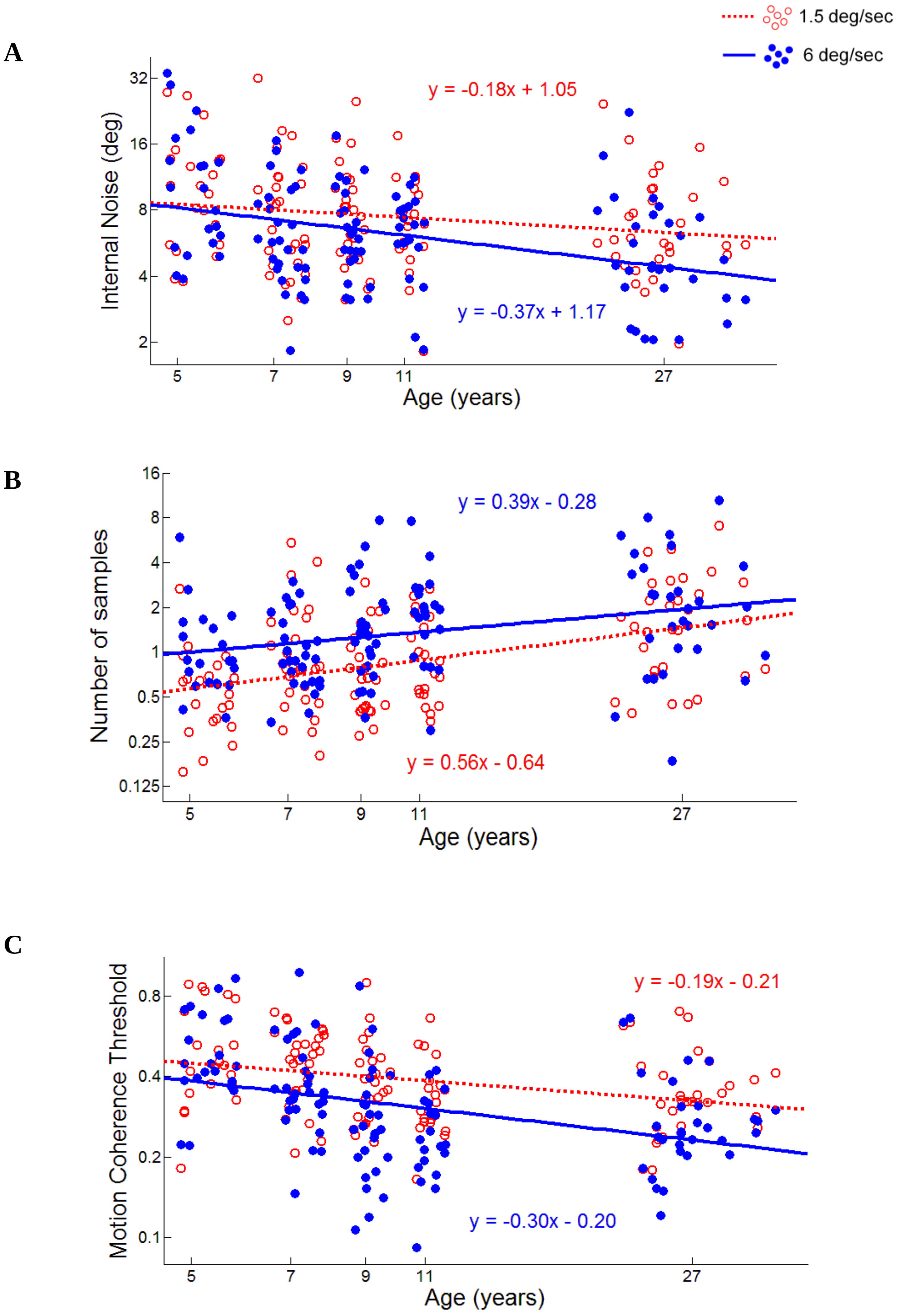


Figure 4.7 Internal noise, sampling and motion coherence thresholds

Individual values for internal noise (**A**), sampling (**B**) and motion coherence thresholds (**C**) for slow (1.5 deg/sec) (open red circles) and fast (6 deg/sec) (filled blue circles) conditions as a function of age. Red dashed and blue solid lines represent the line of best fit for the slow and fast conditions, respectively, and equations are given in log units.

ANCOVA analysis with log age as a covariate showed that internal noise reduced significantly with age, *F*(1, 121) = 13.42, $p < .01$, $\eta_p^2 = .10$. Also, there was a significant interaction between log age and speed condition, *F*(1, 121) = 4.76, $p = .03$, $\eta_p^2 = .04$, indicating a significantly steeper rate of development in the fast condition than the slow condition.

Dunnett *t*-tests were used to determine when adult-like levels of internal noise were reached. In the slow condition, 5-year-olds had significantly higher internal noise than adults ($p = .02$) whereas 7-, 9- and 11-year-olds had adult-like levels of internal noise (*p*s ≥ .51) (5-year-olds: *M* = .98, *SD* = .25; 7-year-olds: *M* = .86, *SD* = .27; 9-year-olds: *M* = .87, *SD* = .23; 11-year-olds: *M* = .83, *SD* = .22; adults: *M* = .83, *SD* = .23). Similarly, in the fast condition, 5-year-olds had higher internal noise than adults ($p < .01$) whereas the older age groups did not (*p*s ≥ .08) (5-year-olds: *M* = .99, *SD* = .28; 7-year-olds: *M* = .78, *SD* = .23; 9-year-olds: *M* = .80, *SD* = .20; 11-year-olds: *M* = .78; *SD* = .21; adults: *M* = .68, *SD* = .26).

4.3.4 Age-related changes in sampling

Next, age-related changes in sampling were investigated. Initial analysis confirmed that the order of conditions did not have a significant effect on sampling estimates, *F*(1, 113) = .60, $p = .44$, and no interactions with group and speed condition, *p*s ≥ .14. As shown in Figure 4.7B, sampling increased from 0.51 at age 5 to 1.47 in adults in the slow condition, and from 0.98 to 1.85 in the fast condition. The ANOVA and ANCOVA analyses were repeated using log sampling as the dependent variable. Higher levels of sampling were obtained in the fast condition (*M* = -.06, *SD* = .34) than in the slow condition (*M* = .13, *SD* = .34), *F*(1, 122) = 39.12, $p < .01$, $\eta_p^2 = .24$. When log age was added into the model as a covariate, it was found that sampling increased across development, *F*(1, 121) = 23.32, *p* < .01, η_p^2 = .16, as predicted. However, there was no interaction between speed condition and log age, *F*(1, 121) = 1.88, *p* = .17, suggesting a similar rate of development in slow and fast conditions.

Dunnett *t*-tests revealed that all child groups had lower sampling compared to adults (*M* = .17, *SD* = .35) in the slow condition (5-year-olds: *M* = -.29, *SD* = .28, *p* < .01; 7-year-olds: M = -.06, SD = .35, *p* < .01; 9-year-olds: *M* = -.15, *SD* = .28, *p* < .01; 11-year-olds: *M* = -.06, *SD* = .28; *p* = .01). In the fast condition, 5-year-olds (*M* = -.01, *SD* = .28) and 7-year-olds (*M* = -.01, *SD* = .25) had lower sampling than adults (*M* = .27, *SD* = .40; *p*s < .01) whereas 9-year-olds (*M* = .14, *SD* = .33) and 11-year-olds (*M* = .23, *SD* = .30) did not differ significantly from adults (*p*s ≥ .67).

4.3.5 Age-related changes in motion coherence thresholds

Preliminary analysis revealed that the order in which slow and fast conditions were presented did not have a main effect on motion coherence thresholds, *F*(1, 113) = .01, *p* = .95, and did not interact with age group, *F*(4, 113) = .32, *p* = .87. However, order interacted with speed condition, *F*(1, 113) = 21.85, *p* < .01, η_p^2 = .16, with a greater difference in thresholds between speed conditions when the slow condition was presented first (slow: *M* = -.38, *SD* = .17; fast: *M* = -.56, *SD* = .19) than when the fast condition was presented first (slow: *M* = -.44, *SD* = .16; fast: *M* = -.48, *SD* = .21). Order was therefore added as a covariate in the ANCOVA analysis reported below.

Whereas 5-year-olds required, on average, 47% coherent motion in both the slow and fast conditions to reliably report the direction of motion, adults required only 34% and 26% coherent motion in the slow and fast conditions, respectively

(Figure 4.7C). An initial ANOVA without covariates revealed higher motion coherence thresholds in the slow condition (*M* = -.41, *SD* = .16) than the fast condition (*M* = -.51, *SD* = .21), *F*(1, 122) = 37.18, $p < .01$, $\eta_p^2 = .23$. Next, ANCOVA analysis was conducted to characterise developmental changes in motion coherence thresholds, with log age and order entered as covariates. Order did not have a significant effect on motion coherence thresholds, *F*(1, 120) = .04, $p = .83$, although it interacted with speed condition, *F*(1,120) = 22.28, $p < .01$, $\eta_p^2 = .16$. Thresholds decreased with log age, *F*(1, 120) = 20.31, $p < .01$, $\eta_p^2 = .15$, but there was no significant interaction between speed condition and log age, *F*(1, 120) = 3.00, $p = .09$, indicating that sensitivity developed at a similar rate for slow and fast speeds.

In the slow condition, 5-year-olds (*M* = -.33, *SD* = .18) and 7-year-olds (*M* = -.35, *SD* = .14) had significantly higher thresholds than adults (*M* = -.47, *SD* = .16; both *p*s < .01), whereas 9-year-olds (*M* = -.42, *SD* = .15) and 11-year-olds (*M* = -.48, *SD* = .14) showed adult-like levels of performance (*p*s ≥ .23). Similarly, in the fast condition, 5-year-olds (*M* = -.32, *SD* = .17) and 7-year-olds (*M* = -.44, *SD* = .17) had higher thresholds than adults (*M* = -.58, *SD* = .17; both *p*s < .01) while 9-year-olds (*M* = -.58, *SD* = .22) and 11-year-olds (*M* = -.63, *SD* = .16) performed at adult-like levels (*p*s ≥ .35).

4.3.6 Relationship between equivalent noise measures and motion coherence thresholds

Thus far, the results show that internal noise reduces, and sampling increases, through development, while motion coherence thresholds decrease. Next I sought to investigate whether increasing sensitivity to coherent motion is driven either by internal noise or sampling, or a combination of both. Correlation analyses including all participants revealed no relationship between internal noise and motion coherence thresholds in either slow, $r(121) = .03$, $p = .77$, or fast, $r(121) = .08$, $p = .36$, conditions. However, sampling was negatively correlated with motion coherence thresholds in both slow, $r(121) = -.35$, $p < .01$, and fast, $r(121) = -.34$, $p < .01$, conditions, whereby greater sampling was associated with lower motion coherence thresholds.

Table 4.1 Results of hierarchical regression analyses on motion coherence thresholds

	Slow condition			**Fast condition**		
	B	**SE B**	**β**	**B**	**SE B**	**β**
Step 1						
Constant	-0.21	0.06		-0.20	0.07	
Log Age	-0.19	.06	-.29**	-0.30	0.07	-.36**
Step 2						
Constant	-0.30	0.06		-0.25	0.07	
Log Age	-0.12	0.06	-.18*	-0.24	0.07	-.29**
Sampling	-0.13	0.04	-.28**	-0.16	0.05	-.26**

Note. Hierarchical regression analyses on motion coherence thresholds in the slow (1.5 deg/sec) and fast (6 deg/sec) conditions.
* $p < .05$, ** $p < .01$. In the slow condition, $R^2 = .09$, $p < .01$ for Step 1; $\Delta R^2 = .06$, $p < .01$ for Step 2. In the fast condition, $R^2 = .13$, $p < .01$ for Step 1; $\Delta R^2 = .06$, $p < .01$ for Step 2.

A hierarchical regression model on motion coherence thresholds was constructed for each speed condition. Due to known age-related changes in motion coherence thresholds (Section 4.3.5), age was entered into the model first, followed by sampling and internal noise added in a stepwise manner (see Table 4.1). No cases of multicollinearity ($r > .90$) were identified in the correlation matrices. Furthermore, all variance inflation factor (VIF) values were under 10 (Myers, 1990) and tolerance statistics above .2 (Menard 1995). Durbin-Watson statistics were acceptable (between 1 and 3) for both models reported below, suggesting that the assumption of independent errors is tenable.

In both slow and fast conditions, age significantly predicted motion coherence thresholds in the first step of the model, *p*s < .01 (Table 4.1). When sampling and internal noise were added into the second step of the model, age remained a significant predictor of motion coherence thresholds, and sampling was also a significant predictor in both slow and fast conditions (*p*s < .01). Internal noise, however, failed to significantly predict coherence thresholds for either speed condition (slow, $\beta = .14$, $p = .16$, or fast, $\beta = .08$, $p = .41$), and was therefore excluded from the model in both speed conditions. Step 2 of the model, with both age and sampling, was a significantly better model than Step 1 of the model in both speed conditions (see Table 4.1). The resulting model with log age and sampling significantly predicted motion coherence thresholds in both slow, $F(2, 120) = 10.63$, $p < .01$, and fast, $F(2, 120) = 14.32$, $p < .01$, conditions.

4.3.7 Fixation results

Next, I investigated whether there were age-related changes in the ability to maintain fixation and whether these were related to task performance. The standard deviation of participants' eye positions for each task is shown in Figure 4.8. A preliminary ANOVA on standard deviations in the equivalent noise task revealed no main effect of noise condition (no-noise, high-noise) and no interactions with age group or speed condition (*p*s ≥ .08), and so this factor was not analysed further.

A mixed ANOVA was conducted on the standard deviations with speed (1.5 deg/sec, 6 deg/sec) and task (equivalent noise, motion coherence) as within-participants factors and age group (5-, 7-, 9- and 11-year-olds and adults) as a between-participants factor. There was no main effect of stimulus speed, $F(1, 54) = 1.34$, $p = .25$. However, higher standard deviations (i.e., reduced stability) were found in the equivalent noise task ($M = -1.08$, $SD = .28$) than the motion coherence task ($M = -1.22$, $SD = .28$), $F(1, 54) = 52.47$, $p < .01$, $\eta_p^2 = .49$. There was a significant main effect of age, *F*(4, 54) = 4.08, *p* < .01, η_p^2 = .23. Dunnett *t*-tests revealed that 5-year-olds had significantly larger standard deviations (*M* = -.92, *SD* = .27) than adults (*M* = -1.27, *SD* = .28), *p* < .01, whereas the older age groups were not significantly different to adults (7-year-olds: *M* = -1.14, *SD* = .27; 9-year-olds: *M* = -1.26, *SD* = .26; 11-year-olds: *M* = -1.19, *SD* = .23; *ps* ≥ .47). No significant interactions were found between task, speed condition and group (*ps* ≥ .42).

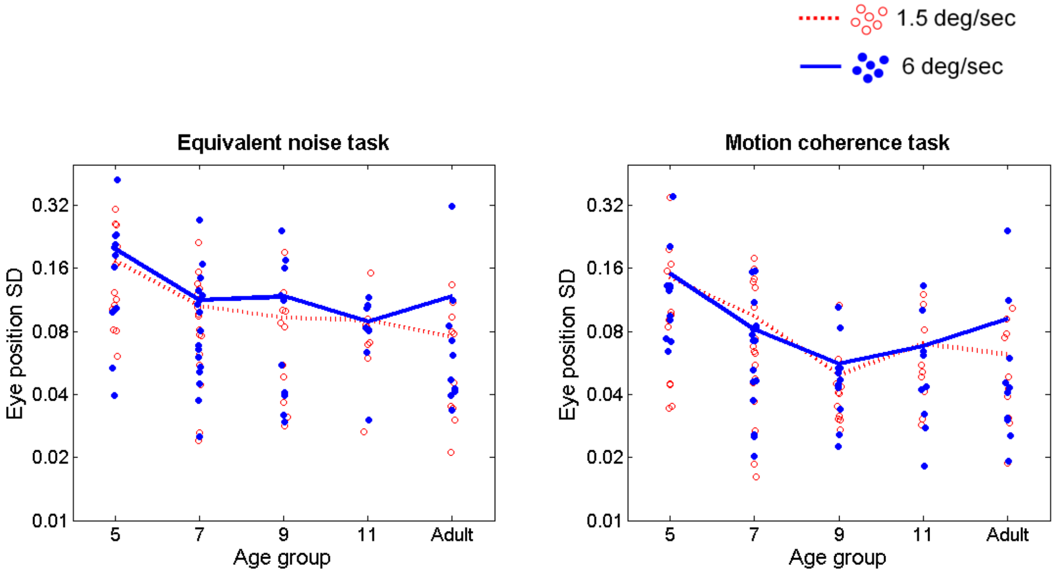


Figure 4.8 Fixation results

Standard deviations of eye positions in equivalent noise tasks (left panel) and motion coherence tasks (right panel) for slow (1.5 deg/sec) and fast (6 deg/sec) speed conditions. Circles show individual performance (slow: open circles; fast: filled circles) and lines represent mean performance for each age group (slow: red dotted line; fast: blue solid line). Standard deviations were log-transformed for analysis.

Having found that the youngest children have less stable fixations than older participants, I sought to investigate whether these differences related to internal noise and sampling[5]. Given that higher levels of internal noise and lower sampling are

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[5] I was primarily interested in how fixation stability related to internal noise and sampling. However, fixation standard deviations were also related to no-noise thresholds in both slow, *r*(57) = .43, *p* < .01, and fast, *r*(57) = .35, *p* < .01, conditions, but not to MTN in either speed condition (*ps* ≥ .31).

found in the slow condition (Section 4.3.3 and 4.3.4), separate analyses were conducted for each speed condition. In the slow condition, fixation standard deviation was related to internal noise estimates, $r(57) = .28$, $p = .04$, with lower fixation standard deviations (i.e., more stable fixations) being associated with lower internal noise. There was, however, no relationship between fixation standard deviation and sampling, $r(57) = -.14$, $p = .29$. Similarly, in the fast condition, fixation standard deviation was related to internal noise, $r(57) = .30$, $p = .02$, but not sampling, $r(57) = -.05$, $p = .72$. Finally, I investigated the relationship between fixation stability and motion coherence thresholds. Motion coherence thresholds were not related to standard deviation of eye positions in either slow, $r(57) = .14$, $p = .31$, or fast, $r(57) = .17$, $p = .20$, conditions.

4.4 Discussion

This study presented an equivalent noise motion integration task alongside a traditional motion coherence task to children aged 5, 7, 9 and 11 years and adults for two speed conditions (slow: 1.5 deg/sec; fast: 6 deg/sec). Age-related improvements in direction discrimination were found both in the absence and presence of noise (directional variability). Modelling these data with equivalent noise functions allowed me to characterise both age-related changes in internal noise and sampling and the mechanisms supporting coherent motion processing. While there was considerable individual variability, it was found that internal noise estimates reduce through childhood, reflecting improved local processing, and that this is accompanied by an increase in the number of samples the child can use to estimate global motion. Note that the effective number of samples can also be thought of as an estimate of multiplicative noise being added to all estimates in the pooling process (i.e., ‘global noise’; Dakin et al., 2005).

Although levels of internal noise reduced with age, these did not predict motion coherence thresholds. Instead, developmental increases in motion coherence sensitivity appear to be driven by age-related increases in sampling. Overall, higher levels of internal noise and lower sampling were found in the slow (1.5 deg/sec) condition than the fast (6 deg/sec) condition, consistent with Bogfjellmo et al. (2014). These differences might reflect distinct speed-tuned motion processing systems (e.g., Thompson et al., 2006; see Section 1.4.1). Generally poorer performance might be a consequence of fewer neurons tuned to slow speeds than fast speeds, as found in the primate brain (Hadad et al., 2011; J. Liu & Newsome, 2003). I was particularly interested, however, in how internal noise and sampling changed with age, and how these age-related effects might vary between speed conditions. Internal noise levels reduced more gradually in the slow (1.5 deg/sec) condition than the fast (6 deg/sec) condition, whereas sampling followed a similar rate of development for slow and fast stimuli. Furthermore, sampling appeared to follow a more protracted rate of development than that of internal noise. Internal noise reached adult-like levels by approximately 7 years of age, while sampling reached adult-like levels at a later age. Indeed, sampling was adult-like by 9 years in the fast condition, but was not yet adult-like by 11 years in the slow condition.

These results complement the findings of Bogfjellmo et al. (2014), which show increased sampling of direction information between the ages of 6 and 17 years for stimulus speeds of 2.8 and 9.8 deg/sec, while levels of internal noise remain stable. Taken together, the current results and those of Bogfjellmo et al. suggest that internal noise reduces to adult-like levels by approximately 6 to 7 years, while age-related changes in sampling follow a more extended trajectory. The finding that internal noise reduces with age concurs with a previous study in the auditory domain which reported higher internal noise in children aged 6 to 11 years compared to adults (Buss et al., 2006), as well as reports of increased levels of internal noise in infants (Skoczenski & Norcia, 1998).

The equivalent noise method gives an estimate of the total amount of internal noise, whilst remaining agnostic about its precise source. However, it is possible that high levels of internal noise in the direction integration task may reflect immaturity in the responses of direction-sensitive cells in V1. Specifically, imprecision in estimating the directions of local elements may be due to broad bandwidths of V1 neurons in children below the age of 7 years, which later narrow with development (at least in the primate brain; Hatta et al., 1998). Conversely, developmental increases in sampling may reflect the development of neurons in higher areas of the motion processing hierarchy thought to be involved in integrating local motion signals, such as MT/V5 (Born & Tootell, 1992; Britten et al., 1992). While MT neurons are responsive to direction information and myelinated at birth in primates (Flechsig, 1901; Movshon et al., 2004), they show immaturities in their integrative properties (Movshon et al., 2004), which could underlie the extended development of sampling reported here. Furthermore, the fact that internal noise matures before sampling corroborates neurophysiological research showing that V1 matures earlier than extrastriate areas (Distler, Bachevalier, Kennedy, Mishkin, & Ungerleider, 1996; Gogtay et al., 2004; Hou et al., 2009; Kourtzi, Augath, Logothetis, Movshon, & Kiorpes, 2006), which has been linked to differences in synaptic pruning (Distler et al., 1996; Gogtay et al., 2004). Future work combining psychophysical and neurophysiological measures is necessary to determine the neural substrate for these effects.

The current findings of age-related reductions in internal noise contrast sharply with McIntosh et al.'s (2008) report of *increasing* neural noise measured by intra-participant EEG variability between the ages of 8 and 12 years. McIntosh et al. suggested that increasing neural noise reflected the brain's increasing complexity with age, allowing one to explore multiple states and adapt to different situations. This sort of complexity, however, is not being tapped by the visual integration task used here, and instead, I refer to internal noise as uncertainty in the coding of local motion directions. Indeed, there are many different sources of noise within the nervous system (Faisal et al., 2008) and it is possible that noise may have different effects at different levels of the cortical hierarchy. However, current computational and neural models of noise are based on animal and human adult brains. It therefore remains a challenge to determine exactly how these models should be applied to the developing brain. The discrepancy between the current results and those of McIntosh et al. highlight the importance of specifying what is meant by noise and the level at which it is thought to have an effect when constructing developmental models.

The current findings add to a body of literature showing a relatively protracted development of sensitivity to coherent motion (Gunn et al., 2002; Hadad et al., 2011). The results suggest that motion coherence thresholds reach adult-like levels by approximately 9 years, which is slightly earlier than previous accounts that have suggested that maturity is reached by 10 to 11 years of age (Gunn et al., 2002), or 12 to 14 years of age (Hadad et al., 2011). Discrepancies in the age at which adult-like levels are reached are likely to be due to differences in a range of stimulus parameters (Meier & Giaschi, 2014; Narasimhan & Giaschi, 2012).

This study also allowed me to test the suggestion that motion coherence sensitivity may mature at different rates for different speeds. While Hadad et al. (2011) did not find a significant difference in the rates of development for sensitivity to coherent motion at 4 deg/sec and 18 deg/sec, Hayward et al. (2011) reported a more gradual rate of development for motion-defined form coherence thresholds at a much slower speed of 0.1 deg/sec compared to faster speeds. While the current results suggest similar rates of development for coherent motion sensitivity at a slow (1.5 deg/sec) and fast (6 deg/sec) speed, two differences between these speed conditions were noted: first that internal noise develops more gradually for slow speeds, and second, that sampling matures later for slow than fast speeds. It is possible that such differences may have contributed to the differential rates of development in coherent motion sensitivity reported in previous studies.

The current study not only describes motion coherence thresholds but also critically helps us to understand what might limit motion coherence sensitivity during development. For the first time, I have shown that age-related improvements in motion coherence sensitivity are driven by an increase in the effective number of local motion signals that are averaged (i.e., improved global integration). In contrast, internal noise does not limit motion coherence thresholds, at least from 5 years of age. This finding complements a recent study by Falkenberg, Simpson and Dutton (2014) showing that sampling, and not internal noise, limits the development of sensitivity to the direction of grating stimuli in children aged 5 to 14 years. It remains an open question, however, as to whether internal noise might limit motion sensitivity earlier on in development. It is also not clear exactly how much internal noise would be needed to limit motion coherence thresholds, as there is no ideal observer model for motion coherence. Dakin et al. (2005) showed that adult observers have higher motion coherence thresholds than would be expected based on estimates of internal noise and sampling alone, which may be due to the additional requirement of segregating signal from noise dots in motion coherence tasks. The ability to extract signal from noise may be another limiting factor on motion coherence sensitivity in development, alongside sampling.

Future work should investigate whether the findings of age-related reductions in internal noise and increases in sampling generalise to different integration tasks, such as orientation integration (e.g., Dakin, 2001), particularly in light of the suggestion that dorsal and ventral processing streams may follow different developmental trajectories (e.g., Braddick et al., 2003). It is also possible that the integration reported here may relate more generally to the ability to average across other types of information, such as multisensory cues, which is also immature in childhood (e.g. Gori, Del Viva, Sandini, & Burr, 2008; Nardini, Bedford, & Mareschal, 2010; Nardini, Jones, Bedford, & Braddick, 2008).

Fixations were measured in a subset of participants, allowing me to establish whether age-related changes in internal noise and sampling were related to differences in the ability to maintain fixation between age groups. Interestingly, fixation stability was related to internal noise, with higher internal noise levels being associated with lower fixation stabilities. A link between eye movements and internal noise has previously been established in a study of people with albinism (Neveu, Jeffery, Moore, & Dakin, 2009), which reported higher levels of internal noise in participants with associated optokinetic nystagmus than those without nystagmus. Neveu et al. (2009) suggested that abnormal eye movements change the structure of visual information entering the system, which therefore disrupts the ability of the motion pathways to form normally. In the current study, the nature of the relationship between fixation stability and internal noise is unclear. It is possible that unstable eye movements limit the precision with which each individual dot's direction can be estimated by young children, or it could be that internal noise estimates and unstable fixation are both indices of increased neural variability. Also, the fixation data suggest that observers use comparable fixation strategies under conditions of low and high noise, which goes some way to support the assumption of noise-invariance of sampling in the equivalent noise model.

The current study used a paradigm that could assess the local and global contributions to motion integration in development – a paradigm that is far more informative than standard motion coherence tasks. The equivalent noise paradigm has been successfully used to study a range of conditions in adult populations, such as amblyopia (Hess, Mansouri, Dakin, & Allen, 2006), glaucoma (Falkenberg & Bex, 2007), migraine (Tibber et al., 2014; Wagner, Manahilov, Loffler, Gordon, & Dutton, 2010), albinism (Neveu et al., 2009) and ageing (Arena, Hutchinson, Shimozaki, & Long, 2013; Bocheva, Angelova, & Stefano, 2013; Pardhan, 2004; Pardhan, Gilchrist, Elliott, & Beh, 1996). The quick, efficient method employed here (and by Tibber et al., 2014) made it feasible to estimate the internal noise and sampling of children. While it is possible that the reduced number of trials may add some measurement error, I have demonstrated that the method is still clearly sensitive to age-related changes. The equivalent noise method is therefore suitable for investigating the atypical development of global motion perception abilities in childhood. In the next chapter, I apply the equivalent noise approach to determine whether elevated motion coherence thresholds in autism can be attributed to atypical local and/or global processing.

5 What limits global motion processing in children with autism?

5.1 Introduction

In Chapter 4, an equivalent noise approach was used to distinguish between local and global limits to direction integration performance in typical development. In typically developing (TD) children, levels of internal noise decrease with age whilst more samples are averaged. However, age-related improvements in motion coherence sensitivity appear to be driven by improvements in sampling and not by reductions in internal noise. Overall, higher levels of internal noise and lower levels of sampling were obtained for slow (1.5 deg/sec) speeds compared to fast (6 deg/sec) speeds.

In Chapter 2, I reported elevated motion coherence thresholds in children with autism, specifically for slow-moving stimuli. Based on the typical developmental trajectories reported in Chapter 4, it might be hypothesised that children with autism show a delayed pattern of development, with elevated motion coherence thresholds resulting from reduced sampling in the slow condition. Certainly, the hypothesis that children with autism average over fewer local elements than TD children is consistent with accounts of weak global processing in autism (e.g., Frith & Happé, 1994; see Section 1.6.2). However, it is also possible that children with autism follow a different pattern of development. Indeed, Simmons et al. (2009) proposed that *increased* levels of internal noise might lead to elevated motion coherence thresholds in autism. Conversely, an alternative account proposes that individuals with autism have *reduced* levels of internal noise compared to typical individuals (G. Davis & Plaisted-Grant, in press; Greenaway et al., 2013).

The equivalent noise paradigm therefore allows us to consider whether atypical levels of internal noise are contributing to atypical global motion perception in children with autism.

In the current study, I presented the same equivalent noise direction integration and motion coherence tasks used in Chapter 4 to children with autism and age- and ability-matched TD children. As in previous chapters, each task was presented at two speed conditions: slow (1.5 deg/sec) and fast (6 deg/sec). Principally, these tasks allowed me to investigate whether motion coherence thresholds are limited by atypical levels of local noise and/or atypical global pooling in children with autism. I hypothesised that children with autism would show elevated motion coherence thresholds, particularly in the slow speed condition (Chapter 2). Furthermore, I predicted that elevated motion coherence thresholds would be predominantly attributable to poor global integration across local estimates as measured by the equivalent noise task, perhaps also in conjunction with atypical levels of internal noise (G. Davis & Plaisted-Grant, in press; Simmons et al., 2009).

5.2 Method

5.2.1 Participants

Forty-one children with autism and 55 TD children aged between 6 and 13 years were recruited from mainstream schools, special schools, autism provisions and community contacts in England. All children with autism had previously received an independent clinical diagnosis of autism or autism spectrum disorder according to ICD-10 criteria (World Health Organisation, 1993). Four children with autism were removed from the dataset as their IQ scores indicated intellectual impairment (verbal IQ [VIQ] < 70 and/or performance IQ [PIQ] < 70) as assessed by the Wechsler Abbreviated Scales of Intelligence (WASI or WASI-II; Wechsler, 1999, 2011; see Section 5.2.2). Two children with autism did not complete all experimental conditions: one due to experimenter error and one due to the fact that a second testing session could not be scheduled. These participants were therefore removed from analysis.

Parents completed the Social Communication Questionnaire (SCQ; Rutter et al., 2003; see Section 2.2.3) and children with autism were administered the Autism Diagnostic Observation Schedule (ADOS-G or ADOS-2; Lord et al., 1999, 2012; see Section 5.2.2). As in Chapter 2, only those who scored above threshold for an autism spectrum condition on at least one of these two measures were included in the dataset. Two children with autism were removed from the dataset as they did not meet the autism spectrum cut-off on either measure. All TD children scored below the cut-off for autism spectrum on the SCQ (< 15; Rutter et al., 2003). One TD child was removed from the dataset due to having a diagnosis of a developmental condition (dyspraxia). Letter acuity charts were used to confirm normal or corrected-to-normal visual acuity, using optical corrections where necessary. All children were assessed using a Snellen chart apart from two children with autism and 12 TD children who were assessed with Cambridge Crowding Cards. Normal acuity was defined as a binocular acuity of 6/9 or better for children aged 7 to 8 years and 6/6 or better for older children. One TD child was removed from the dataset for this reason.

Thirty-three children with autism (M=10 years; 3 months, range 5;11 – 13;0, 3 females) were therefore included in the final dataset. Thirty-three TD children (M=9 years; 11 months, range 6;0 - 13;1, 10 females) were selected to match the children with autism on an individual basis. The resulting groups did not differ in terms of chronological age, *t*(64) = .40, *p* = .69, PIQ, *t*(64) = .26, *p* = .80, or VIQ, *t*(64) = 1.44, *p* = .16. Participant demographics of children included in the final dataset are provided in Table 5.1. Eleven participants with autism had additional diagnoses of developmental conditions. Eight children with autism had diagnoses of attention deficit/hyperactivity disorder (AD/HD), with four of these also reporting one or more additional conditions (including tic disorders, dyslexia and dyspraxia). Three participants with autism had diagnoses of dyslexia, sensory processing disorder and dyspraxia, respectively, without a co-occurring diagnosis of AD/HD. Nine of the children with autism had participated in the study reported in Chapter 2, and 33 TD children were also included in the analysis presented in Chapter 4.

Table 5.1 Participant characteristics

Measures	*Children with autism*	*Typically developing children*
n	33	33
Gender (*n* males: *n* females)	30:3	23:10
Age (years;months)		
Mean (SD)	10;2 (2;0)	9;11 (1;9)
Range	5;11 – 13;0	6;0 – 13;1
Verbal IQ		
Mean (SD)	98.39 (9.92)	102.00 (10.48)
Range	80 – 120	76 – 118
Performance IQ		
Mean (SD)	105.21 (15.35)	104.33 (11.99)
Range	72 – 137	84 – 131
Full-scale IQ		
Mean (SD)	102.03 (12.15)	103.58 (10.10)
Range	75 – 127	85 – 124
Mother's age on leaving full-time education		
Mean (SD)	21.42 (3.53)	21.73 (5.72)
Range	15 – 30	12 – 40
SCQ score		
Mean (SD)	24.77 (7.50)	4.71 (4.32)
Range	5 – 38	0 – 14
ADOS social affect		
Mean (SD)	8.97 (4.95)	
Range	0 – 18	
ADOS restricted and repetitive behaviour		
Mean (SD)	1.97 (1.53)	
Range	0 – 6	
ADOS Total Score		
Mean (SD)	10.94 (5.73)	
Range	2 – 23	

Note. SCQ = Social Communication Questionnaire (Rutter et al., 2003); ADOS = Autism Diagnostic Observation Schedule (Lord et al., 1999, 2012).

Of all parents of children included in the final dataset, SCQ and background questionnaires (see Section 2.2.2) were returned by 31 parents of children with autism and 28 parents of TD children. The majority of parents reported being White British, both in the autism group (*n* = 25) and TD group (*n* = 16). Other ethnic backgrounds reported in the autism group were Mixed White and Black Caribbean (*n* = 1), Latin American (*n* = 1), Black Caribbean (*n* = 1), Indian (*n* = 2) and White American French (*n* = 1), and in the TD group, Black African (*n* = 4), Middle Eastern (*n* = 1), White Irish (*n* = 2) and other White backgrounds (*n* = 5). The mother's age on leaving full-time education did not differ between groups, $t(55) = .25$, $p = .80$[6] (see Table 5.1 for group means).

5.2.2 Standardised measures

Since designing the study and collecting the data for Chapter 2, updated versions of the WASI (WASI-II; Wechsler, 2011) and ADOS (ADOS-2; Lord et al., 2012) had been published. Therefore, WASI-II and ADOS-2 measures were used for children that were not tested previously (Section 5.2.1). The WASI-II is highly correlated with the WASI (Wechsler, 2011), and the revised algorithm of the ADOS (Gotham, Risi, Pickles, & Lord, 2007; Gotham et al., 2008) was applied to all ADOS data to ensure comparability between ADOS-2 and ADOS-G. The revised algorithm yields scores for social affect and restricted and repetitive behaviour (see Table 5.1), which are combined to give a total score. All children with autism in this study were

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[6] Two parents of TD children who returned background questionnaires did not provide the mother's age on leaving full-time education.

administered Module 3 of the ADOS-G or ADOS-2. The cut-off for autism spectrum for Module 3 in the revised algorithm is a total score of 7[7].

5.2.3 Experimental procedure

The apparatus, stimuli and tasks were the same as described in Chapter 4. Children completed an equivalent noise direction integration task (with interleaved no-noise and high-noise conditions) and a motion coherence task in both slow (1.5 deg/sec) and fast (6 deg/sec) speed conditions. White random dot stimuli of unlimited lifetime drifted within a circular aperture for 400 ms, and participants were asked to report the overall direction of motion. As in Chapter 4, five performance measures were obtained: i) no-noise thresholds, ii) maximum level of tolerable noise (MTN) estimates, iii) internal noise, iv) sampling, and v) motion coherence thresholds (see Sections 4.2.3 and 4.2.6.1).

5.2.4 Eyetracking

To investigate whether group differences in performance could be attributed to differences in the ability to maintain fixation, a Tobii X2-30 Compact eyetracker mounted onto the screen collected fixation data for a subset of participants including 23 children with autism (two females) and 22 TD children (six females). A five-point calibration procedure was conducted before the introductory phase and fixation

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[7] Note that revised algorithm scores could not be computed for one child with autism. This child had been assessed with the ADOS-G by a clinician as part of the diagnostic process within a month prior to the testing session, and therefore the ADOS assessment was not repeated. The parent provided Communication and Social Interaction subscale scores from the clinician's report, which showed that the child met criteria for autism using the original cut-offs.

data were sampled at a rate of 40 Hz during stimulus presentation in the threshold estimation phase.

5.2.5 General procedure

The procedure was approved by the Institute’s Faculty Research Ethics Committee. Parents gave their informed consent and children verbally assented. As described in Chapter 4, the experimental tasks were presented in two separate sessions, with each session consisting of one condition of the equivalent noise task and one condition of the motion coherence task. The order of presentation of these conditions was counterbalanced between participants. Children who had not been tested previously were administered the WASI-II, acuity test and the ADOS-2 in further sessions, resulting in three testing sessions lasting approximately 30 minutes for TD children, and four testing sessions lasting 30 to 45 minutes for children with autism.

5.2.6 Data screening and transformation

All participants passed criterion in the criterion phase (Section 4.2.3.1) and performed significantly above chance in the catch trials indicating that they understood the task requirements. There was no effect of group on the proportion of incorrect responses to catch trials, $F(1, 64) = 1.74$, $p = .19$, and group did not interact with speed condition, $F(1, 64) = .05$, $p = .83$, or task, $F(1, 64) = .07$, $p = .79$. Therefore, lapse rate was not corrected for in the threshold estimates, unlike in Chapter 4 (Section 4.2.6.2). One child with autism obtained a motion coherence threshold above 1 in the slow condition, indicating an inability to perform the task, and was therefore removed from the motion coherence analysis.

The majority of measures showed significant skew and kurtosis (*p*s < .05), which was minimised by log-transforming the data. The data were then screened for potential outliers, defined as data-points lying more than ±3 SD from the group mean performance for each speed condition. Three outliers were identified: one in the no-noise threshold of a child with autism in the fast condition, one in the MTN estimate of a TD child in the slow condition, and one corresponding to the sampling estimate from a TD child in the fast condition. Removing these outliers did not change the pattern of the results and so these points were retained to maintain statistical power but replaced with values corresponding to ±2.5 SD from the group mean (Tabachnick & Fidell, 2007; see also Sections 2.2.7 and 4.2.6.2). All of the analyses reported below were conducted with log-transformed values. For ease of interpretation, linear units are displayed in all figures.

5.2.7 Fixation analysis

As described in Section 4.2.6.3, the (x,y) coordinates of fixations were filtered and pooled to obtain standard deviations indexing fixation stability. The standard deviations were log-transformed for analysis and screened for outliers, defined as data points lying more than ±3SD from the group mean for each task condition. No outliers were found.

5.3 Results

5.3.1 No-noise thresholds

No-noise thresholds for children with autism and TD participants are presented in Figure 5.1A. Preliminary analysis revealed no effect of the order in which participants completed slow and fast conditions on no-noise thresholds, *F*(1, 62) = 3.38, *p* = .07, nor interactions between group (autism, TD) and speed condition (1.5 deg/sec, 6 deg/sec), *ps* ≥ .19. This factor was therefore not included in further analysis.

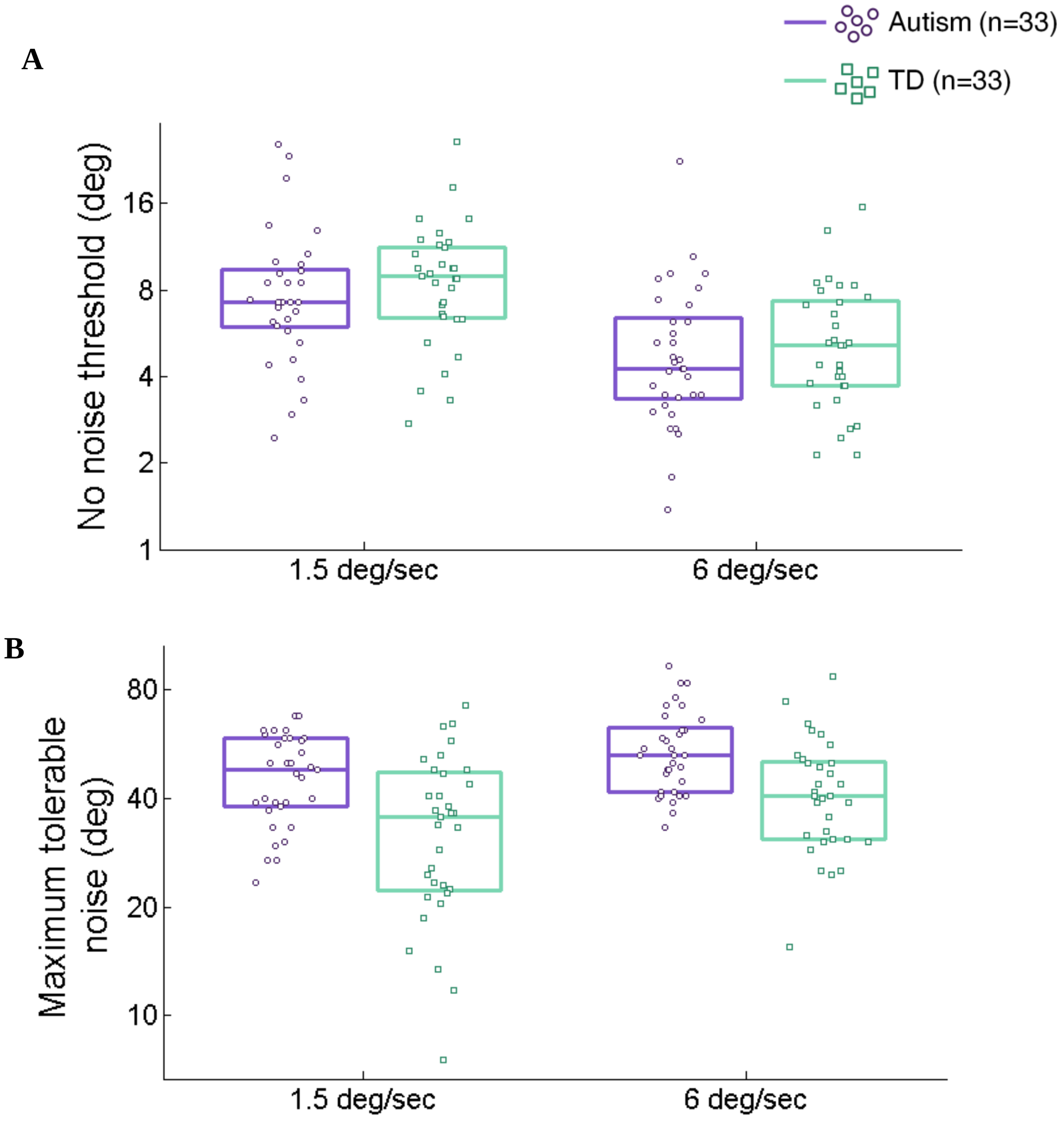

Figure 5.1. No-noise thresholds and maximum level of tolerable noise (MTN) values

Individual no-noise direction discrimination thresholds **(A)** and MTN values **(B)** for children with autism (purple circles) and typically developing children (TD; green squares) in slow (1.5 deg/sec) and fast (6 deg/sec) speed conditions. Box plots represent median values and interquartile ranges for each group. N.b. Data are presented with outliers replaced (Tabachnick & Fidell, 2007).

A mixed-design analysis of variance (ANOVA) on thresholds was conducted with group (autism, TD) as the between-participants factor and speed condition (1.5 and 6 deg/sec) as the within-participants factor. Before entering age and full-scale IQ (FSIQ) as covariates, the within-participants effect of speed was confirmed in the absence of covarying variables (Delaney & Maxwell, 1981). Overall, lower thresholds were obtained in the fast condition ($M = .68$, $SD = .23$) than the slow condition ($M = .90$, $SD = .22$), $F(1, 64) = 104.15$, $p < .01$, $\eta_p^2 = 62$. When entered as a covariate, age had a significant effect on no-noise thresholds, $F(1, 62) = 15.53$, $p < .01$, $\eta_p^2 = .20$, with older children having lower thresholds. However, FSIQ did not have a significant effect on no-noise thresholds, $F(1,62) = 3.28$, $p = .08$, $\eta_p^2 = .05$. Neither age nor FSIQ interacted with speed condition. When controlling for age and FSIQ, there was no main effect of group, with children with autism having similar no-noise thresholds ($M = .77$, $SD = .26$) as TD children ($M = .81$, $SD = .24$), $F(1, 62) = .76$, $p = .39$. Furthermore, there was no significant interacting effect between speed condition and group, $F(1, 62) = .06$, $p = .80$.

5.3.2 Maximum tolerable noise (MTN)

The amount of noise that could be tolerated (MTN) in the high-noise condition is shown in Figure 5.1B. The order in which participants completed slow and fast conditions of the equivalent noise task had no effect on MTN, $F(1, 62) = .49$, $p = .49$, and did not interact with group and speed condition, $p\text{s} \geq .34$. Order was therefore not analysed further. Overall, more noise could be tolerated in the fast condition ($M = 1.67$, $SD = .15$) than the slow condition ($M = 1.57$, $SD = .20$), $F(1, 64) = 11.12$, $p < .01$, $\eta_p^2 = .15$. While age and FSIQ did not have a significant effect on MTN and did not interact with speed condition, $p\text{s} \geq .09$, these were retained as covariates for consistency with other analyses. There was a main effect of group, with children with autism having higher MTN values (i.e., being able to tolerate *more* noise than TD children; autism: *M* = 1.69, *SD* = .13; TD: *M* = 1.55, *SD* = .20), *F*(1, 62) = 16.89, *p* < .01, η_p^2 = .21. However, the effect of group did not interact with speed condition, *F*(1, 62) = .46, *p* = .50.

5.3.3 Internal noise

Next, the results of the equivalent noise modelling were analysed in order to determine the extent to which local and/or global processing limit direction integration performance in children with autism. Figure 5.2A shows internal noise estimates for each speed condition. Preliminary analysis confirmed that the order of conditions did not have a significant effect on internal noise estimates, *F*(1, 62) = 1.99, *p* = .16, and no interactions with group or speed condition, *p*s ≥ .57. ANOVA analysis showed that higher internal noise estimates were obtained in the slow condition (*M* = .86, *SD* = .23) than the fast condition (*M* = .73, *SD* = .26), *F*(1, 64) = 20.18, *p* < .01, η_p^2 = .24. Age and FSIQ were then added as covariates. Age had a significant effect on internal noise estimates, *F*(1, 62) = 9.34, *p* < .01, η_p^2 = .13, with older children having lower levels of internal noise. In contrast, FSIQ did not have a significant effect on internal noise estimates, *F*(1, 62) = 2.75, *p* = .10. Neither covariate had an interacting effect with speed condition, *p*s ≥ .13. There was no significant group difference in internal noise estimates, *F*(1, 62) = 2.75, *p* = .10, and no significant interacting effect between speed condition and group, *F*(1, 62) = .52, *p* = .47.

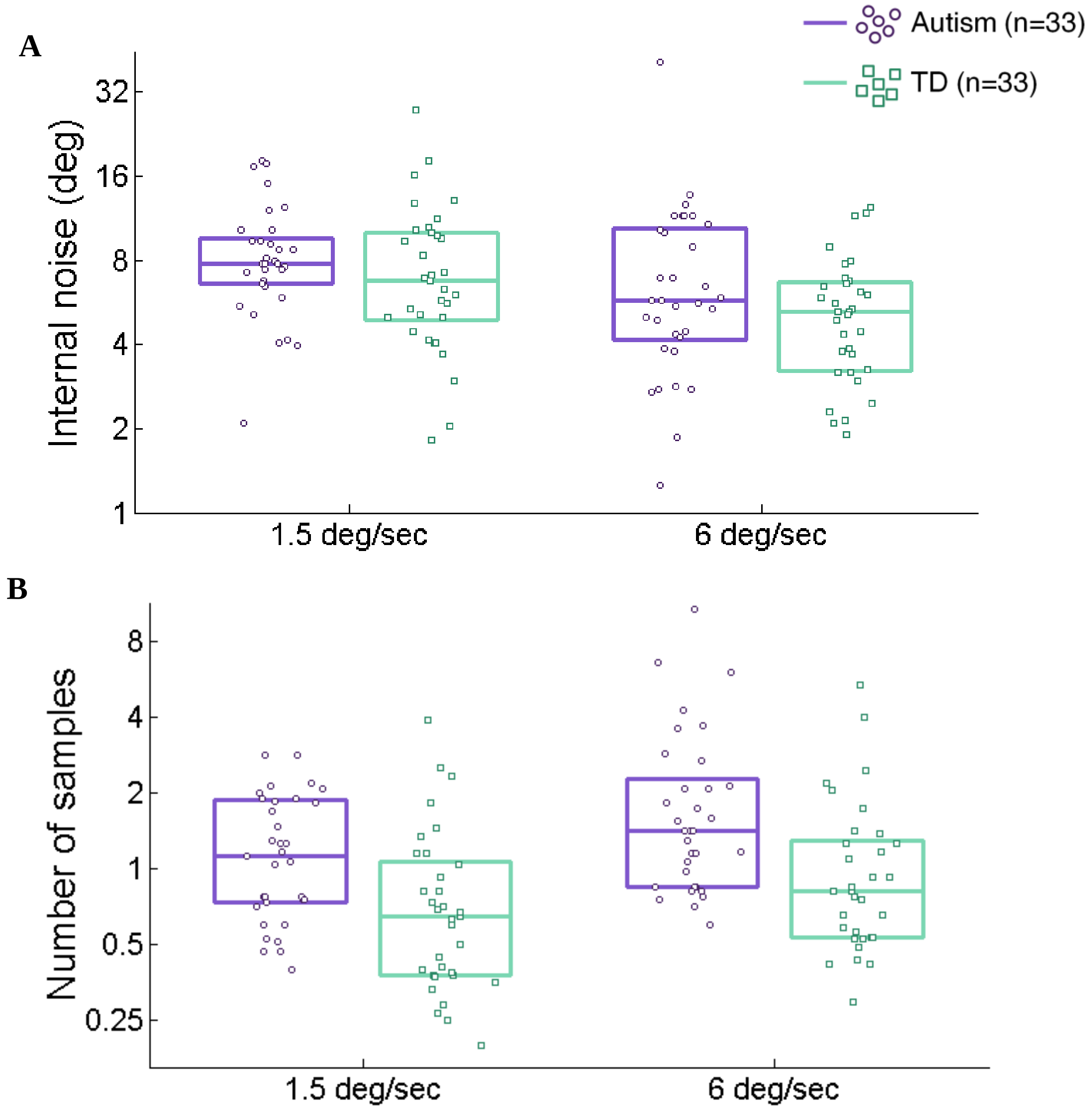

Figure 5.2 Estimates of internal noise and sampling

Individual estimates of internal noise (A) and sampling (B) from equivalent noise analysis for children with autism (purple circles) and typically developing children (TD; green squares) in slow (1.5 deg/sec) and fast (6 deg/sec) speed conditions. Box plots represent median values and interquartile ranges for each group. N.b. Data are presented with outliers replaced (Tabachnick & Fidell, 2007).

5.3.4 Sampling

Estimates of sampling for each speed condition are shown in Figure 5.2B. Order of speed conditions had no significant effect on sampling estimates, *F*(1, 62) = .53, *p* = .47, and no interactions with speed condition or group, *ps* ≥ .12, and was therefore not analysed further. A mixed design ANOVA revealed a significant effect of speed condition, *F*(1, 64) = 18.18, *p* < .01, η_p^2 = .22, with greater sampling in the fast condition (*M* = .09, *SD* = .32) compared to the slow condition (*M* = -.07, *SD* =

.30). Next, age and FSIQ were entered as covariates. Neither age nor FSIQ had a significant effect on sampling estimates (age: *F*[1, 62] = 1.09, *p* = .30; FSIQ: *F*[1, 62] = .42, *p* = .52), although there was a marginal interaction between FSIQ and speed condition, *F*(1, 62) = 4.11, *p* = .05, η_p^2 = .06. There was a significant group difference, with children with autism having increased sampling (*M* = .12, *SD* = .29) compared to TD children (*M* = -.11, *SD* = .31), *F*(1, 62) = 14.13, *p* < .01, η_p^2 = .19. There was no interaction effect between speed condition and group, *F*(1, 62) = .45, *p* = .50.

5.3.5 Motion coherence thresholds

Motion coherence thresholds for each group in each speed condition are shown in Figure 5.3. The order of presentation of slow and fast conditions of the motion coherence task had a significant effect on thresholds, *F*(1, 61) = 4.56, *p* = .04, η_p^2 = .07, with lower thresholds being obtained when the slow condition was presented first (*M* = -.54, *SD* = .19), compared to when the fast condition was presented first (*M* = -.46, *SD* = .17). Also, order had a significant interacting effect with speed condition, *F*(1, 61) = 14.03, *p* < .01, η_p^2 = .19, with a greater difference between speed conditions when the slow condition was presented first (slow: *M* = -.42, *SD* = .13; fast: *M* = -.65, *SD* = .18) than when the fast condition was presented first (slow: *M* = -.41, *SD* = .16; fast: *M* = -.51, *SD* = .17).

Order was therefore retained as a covariate when investigating between-participants effects, along with age and FSIQ. First, however, the within-participants effect of speed was investigated without covariates. Overall, higher motion coherence thresholds were obtained in the slow condition (*M* = -.42, *SD* = .14), than the fast condition (*M* = -.59, *SD* = .19), *F*(1, 63) = 68.05, *p* < .01, η_p^2 = .52. Next, age, FSIQ and order were added as covariates into the ANOVA. In addition to order, *F*(1, 60) = 4.59, *p* = .04, η_p^2 = .07, age had a significant effect on motion coherence thresholds, *F*(1, 60) = 6.67, *p* = .01, η_p^2 = .10. FSIQ did not have a significant effect on motion coherence thresholds, *F*(1, 60) = 2.91, *p* = .09. Order interacted with speed condition, *F*(1, 60) = 13.26, *p* < .01, η_p^2 = .18, whereas age and FSIQ did not, *p*s ≥ .53. There was no significant group difference in thresholds, *F*(1, 60) = .16, *p* = .69, and no significant interaction between group and speed, *F*(1, 60) = .06, *p* = .81.

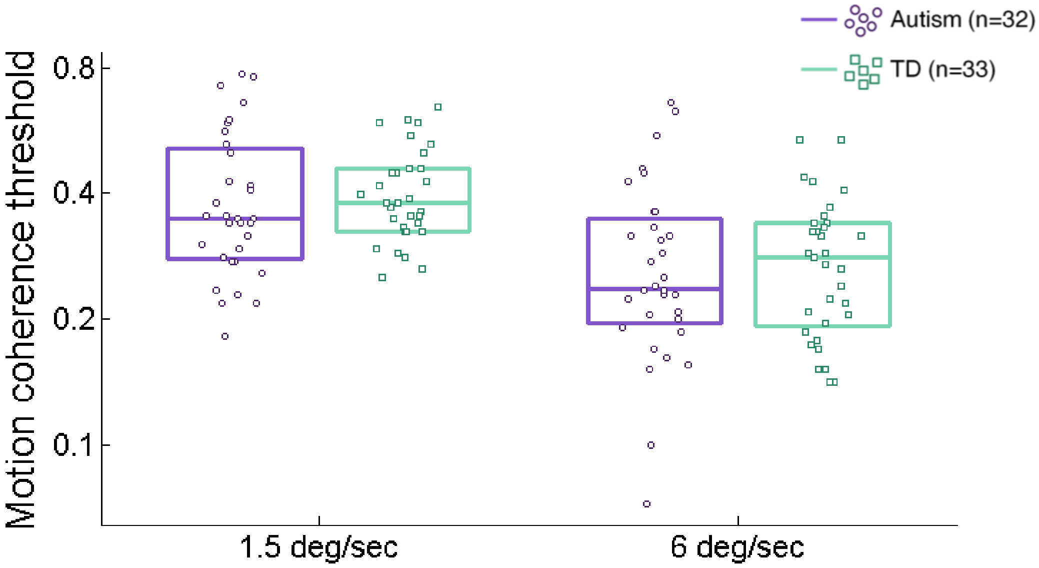

Figure 5.3 Motion coherence thresholds

Proportion of coherently moving dots required for accurate direction discrimination for children with autism (purple circles) and typically developing children (TD; green squares). Box plots represent median values and interquartile ranges for each group.

5.3.6 Relating performance to developmental trajectories in Chapter 4

As reported above (Sections 5.3.2 and 5.3.4), children with autism had higher values of MTN and sampling than TD children of similar age and ability. In Chapter 4, I showed that MTN and sampling values increased in typical development with age, suggesting that children with autism may be performing like older observers.

To address this, I compared the performance of the groups of children with autism and TD children with the developmental trajectory reported in Chapter 4.

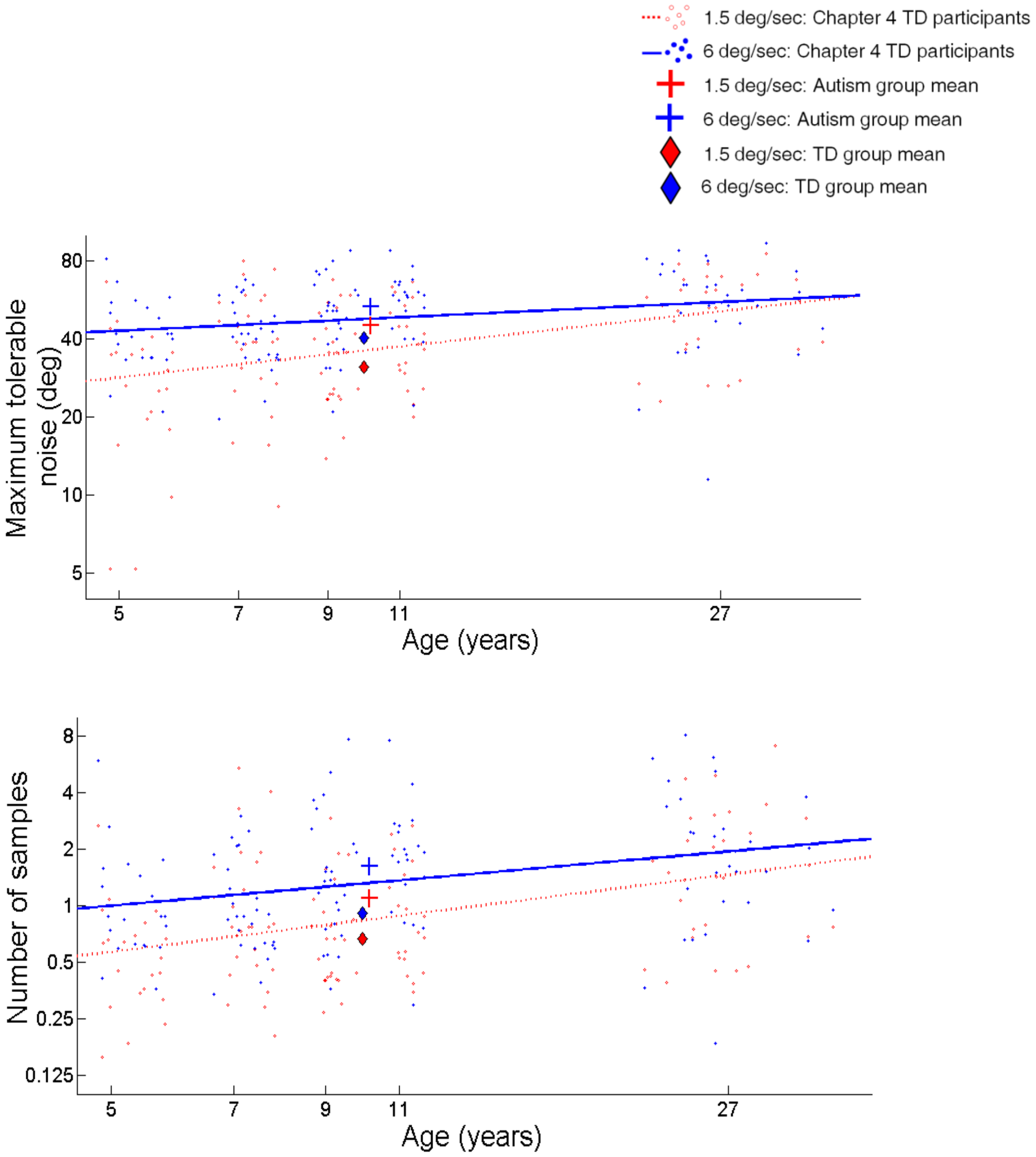

Figure 5.4 Mean maximum tolerable noise (MTN) and sampling in relation to TD data from Chapter 4.

Group mean levels of MTN (upper panel) and sampling (lower panel) superimposed on TD data reported in Chapter 4 (Figure 4.6B and Figure 4.7B). Crosses represent the mean level of performance for children with autism and diamonds represent the mean level of performance for the age- and ability matched TD children in slow (red) and fast (blue) conditions. The dots and lines represent individual values and regression lines for participants tested in the study reported in Chapter 4, for slow (red) and fast (blue) conditions.

Figure 5.4 plots the group mean levels of MTN and sampling performance for the matched groups of children with autism and TD children in the current study against the individual data points and developmental trajectories of the TD data reported in Chapter 4. Inspection of this figure suggests that children with autism have higher levels of MTN and sampling than would be expected for their age. Next, I added the adult group from Chapter 4 into the analyses, in order to determine whether the children with autism and matched TD children were performing at adult-like levels. Note that age and FSIQ were not covaried out here, because I was explicitly testing age-related changes between the child and adult groups, and because IQ scores were not obtained from adults recruited in the previous study (Chapter 4).

A mixed ANOVA on no-noise thresholds with group (autism, TD, adult) as a between-participants factor and speed (1.5 deg/sec, 6 deg/sec) as a within-participants factor revealed a group difference in no-noise thresholds, $F(2, 93) = 6.49$, $p < .01$, $\eta_p^2 = .12$. Dunnett *t*-tests corrected for multiple comparisons revealed that both children with autism and TD children had significantly higher no-noise thresholds than adults ($M = .64$, $SD = .21$; autism: $p = .02$, TD: $p < .01$). Next, this analysis was repeated on MTN values. Again, there was a significant group difference in MTN values, $F(2, 93) = 12.17$, $p < .01$ $\eta_p^2 = .21$. Dunnett's *t*-tests showed that TD children had significantly lower MTN values than adults ($M = 1.71$, $SD = .18$), $p < .01$, whereas children with autism performed at adult-like levels, $p = .74$.

Next these analyses were repeated on the estimates obtained from equivalent noise analysis: internal noise and sampling. There was no overall group difference in internal noise values, $F(2, 93) = 1.49$, $p = .23$, suggesting that both child groups have adult-like levels of internal noise. However, there was a significant group difference in sampling estimates, $F(2, 93) = 11.35$, $p < .01$, $\eta_p^2 = .20$. TD children had significantly lower values of sampling than adults ($M = .22$, $SD = .38$), $p < .01$, whereas the children with autism had comparable levels as the adult group, $p = .32$. Next, this analysis was repeated on motion coherence thresholds, which showed no overall difference between the three participant groups, $F(2, 92) = .37$, $p = .69$. For all ANOVA analyses reported here, there was a significant effect of speed condition, as expected (ps < .01), and no group by speed interaction (ps ≥ .19).

5.3.7 Relationship between equivalent noise measures and motion coherence thresholds

Table 5.2 Correlations between motion coherence thresholds and internal noise and sampling estimates

	Bivariate				*Partial (age, full-scale IQ)*			
	Children with autism		*Typically developing children*		*Children with autism*		*Typically developing children*	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
1.5 deg/sec								
Internal noise	**.47 [a]**	**< .01**	.07 [b]	.68	**.39 [c]**	**.03**	-.07 [d]	.73
Sampling	**-.46 [a]**	**< .01**	-.11 [b]	.56	**-.44 [c]**	**.01**	-.07 [d]	.69
6 deg/sec								
Internal noise	-.03 [a]	.89	.24 [b]	.19	-.07 [c]	.70	< .01 [d]	.99
Sampling	**-.68 [a]**	**< .01**	-.35 [b]	.05	**-.70 [c]**	**< .01**	-.29 [d]	.11

Note. The left panel shows bivariate correlations between motion coherence thresholds and internal noise and sampling estimates in slow (1.5 deg/sec) and fast (6 deg/sec) speed conditions, for children with autism and typically developing children. The right panel shows these correlations once age and full-scale IQ have been partialled out. Significant correlations ($p < .05$) are highlighted in boldface.
[a] $df = 30$, [b] $df = 31$, [c] $df = 28$, [d] $df = 29$.

Next I sought to establish whether levels of internal noise and sampling were related to motion coherence thresholds. Bivariate correlations are provided in the left panel of Table 5.2. When controlling for the effect of age and FSIQ, sampling was related to motion coherence thresholds for children with autism in the slow and fast conditions (ps ≤ .01, see Table 5.2, right panel), whereby greater sampling was associated with lower motion coherence thresholds. Sampling was not significantly related to motion coherence thresholds in the TD group once controlling for age and FSIQ (*p*s $\geq$ .11; Table 5.2, right panel). Internal noise was related to motion coherence thresholds in the slow condition for children with autism ($p = .03$), whereby higher levels of internal noise were associated with higher motion coherence thresholds. No other relationships between internal noise and motion coherence were significant once controlling for age and FSIQ (*p*s $\geq$ .70; Table 5.2).

Next, I built regression models on motion coherence thresholds in the slow and fast conditions for children with autism and TD children (Table 5.3). In Chapter 4, hierarchical regression analyses were used with age entered into the model before sampling and internal noise, based on the results of the ANCOVA analyses (Section 4.3.5) and previous studies showing age-related changes in motion coherence thresholds in TD children (e.g., Gunn et al., 2002; Hadad et al., 2011). However, the relationship between age and motion coherence thresholds in children with autism is less clear. Therefore, a backward stepwise method was used in this study[8], whereby all predictors were initially placed in the model, and those that did not make statistically significant contributions to the model were removed. The predictor variables used were age, FSIQ, sampling and internal noise. No cases of multicollinearity ($r > .90$) were identified in the correlation matrices. Furthermore, all variance inflation factor (VIF) values were under 10 (Myers, 1990) and tolerance statistics above .2 (Menard 1995). Durbin-Watson statistics were acceptable (between 1 and 3) for all models reported below, suggesting that the assumption of independent errors is tenable.

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[8] The backward method was used rather than the forward method in order to reduce the probability of excluding predictors involved in suppressor effects (Field, 2005).

First, I investigated the predictors of motion coherence thresholds in the slow condition for children with autism. The first step of the model, which included all predictor variables (Table 5.3), provided a significant fit to the data, explaining 45.1% of the variation in motion coherence thresholds, $F(4, 27) = .5.55$, $p < .01$. Age was removed in the second step of the model as it was not a significant predictor of motion coherence thresholds ($\beta = .07$, $p = .66$), and similarly, FSIQ was removed in the third step of the model ($\beta = -.08$, $p = .60$). For children with autism, sampling and internal noise were retained as predictors of motion coherence thresholds in the final model, $F(2, 29) = 11.46$, $p < .01$ (see Table 5.3), with sampling negatively predicting motion coherence thresholds and internal noise positively predicting thresholds. Removal of age and FSIQ did not significantly reduce the amount of variance explained by the model (see Table 5.3 for R^2 values), and the final model explained 44.2% of the variance in motion coherence thresholds in the slow condition for children with autism.

Next, regression analyses were conducted on the motion coherence thresholds in the fast condition for children with autism. The first step of the model including all predictor variables provided a significant fit to the data, $F(4, 27) = 7.96$, $p < .01$. FSIQ was removed in the second step of the model as it was not a significant predictor ($\beta = .01$, $p = .95$), and age was removed in the third step of the model ($\beta = -.01$, $p = .94$). Removal of these variables did not significantly reduce the amount of variance explained by the model (Table 5.3). Therefore, internal noise and sampling were retained in the final model for children with autism, as in the slow condition. The final model explained 54.1% of the variance in motion coherence thresholds in the fast condition for children with autism, $F(2, 29) = 17.08$, $p < .01$.

Next, I investigated the predictors of motion coherence thresholds for TD children. In the slow condition, the first step of the model with all predictor variables did not significantly fit the data, *F*(4, 28) = 2.41, *p* = .07. Internal noise and sampling were removed in the second and third steps of the model, respectively, as they were not significant predictors (internal noise: β = -.03, *p* = .89; sampling: β = -.06, *p* = .69). FSIQ was removed in the final step of the model (β = -.13, *p* = .43), leaving age as the only significant predictor of motion coherence thresholds (Table 5.3). Age was a negative predictor of motion coherence thresholds, indicating that older children have lower thresholds. The removal of internal noise, sampling and FSIQ did not affect the amount of variance explained by the model (Table 5.3). The final model provided a significant fit to the data, *F*(1, 31) = 9.52, *p* < .01, and explained 23.5% of the variance in motion coherence thresholds in the slow condition for TD children.

In the fast condition, the first step of the model with all predictor variables was significant, *F*(4, 28) = 4.32, *p* < .01. In the second stage of the model, internal noise was removed as it was not a significant predictor (β = .18, *p* = .35), and in the third stage of the model, sampling was removed (β = -.24, *p* = .13). The final model consisted of age and FSIQ, which explained 30.9% of the variance in motion coherence thresholds in the fast condition for TD children, *F*(2, 30) = 6.70, *p* < .01. Age and FSIQ were negative predictors, such that older children and children with higher FSIQ scores had lower thresholds. Removal of internal noise and sampling did not reduce the amount of variance explained by the model (Table 5.3).

Table 5.3 Regression analyses on motion coherence thresholds

	Children with autism						*Typically developing children*					
	Slow condition [a]			*Fast condition* [b]			*Slow condition* [c]			*Fast condition* [d]		
Model Step	B	SE B	β	B	SE B	β	B	SE B	β	B	SE B	β
Step 1												
Constant	-.71	.32		-.65	.29		.05	.26		.02	.40	
Age	.01	.01	.07	<-.01	.02	-.01	-.03	.01	-.49**	-.03	.02	-.36*
FSIQ	< -.01	<.01	-.09	<.01	<.01	.01	< -.01	<.01	-.14	<-.01	<.01	-.22
Internal noise	.40	.14	.47**	.22	.11	.31	-.01	.09	-.03	.14	.14	.18
Sampling	-.33	.10	-.49**	-.55	.10	-.81**	-.05	-.23	.82	-.18	.10	-.32
Step 2												
Constant	-.64	.28		-.63	.20		.03	.21		.28	.30	
Age	-	-	-	<-.01	.02	-.01	-.03	.01	-.48**	-.04	.01	-.44**
FSIQ	<-.01	<.01	-.08				< -.01	<.01	-.13	<.01	<.01	-.27
Internal noise	.38	.13	.45**	.22	.11	.31	-	-	-	-	-	-
Sampling	-.32	.10	-.47**	-.55	.10	-.81**	-.02	.06	-.06	-.14	.09	-.24
Step 3												
Constant	**-.78**	**.11**		**-.65**	**.08**		.03	.21		**.39**	**.30**	
Age	**-**	**-**	**-**	**-**	**-**	**-**	-.03	.01	-.49**	**-.04**	**.01**	**-.46****
FSIQ	**-**	**-**	**-**	**-**	**-**	**-**	< -.01	<.01	-.13	**-.01**	**<.01**	**-.32***
Internal noise	**.41**	**.12**	**.48****	**.23**	**.10**	**.32***	-	-	-	**-**	**-**	**-**
Sampling	**-.32**	**.09**	**-.47****	**-.55**	**.09**	**-.81****	-	-	-	**-**	**-**	**-**
Step 4												
Constant							**-.11**	**.10**				
Age							**-.03**	**.01**	**-.49****			
FSIQ							**-**	**-**	**-**			
Internal noise							**-**	**-**	**-**			
Sampling							**-**	**-**	**-**			

Note. Backward stepwise regression analyses on motion coherence thresholds in the slow (1.5 deg/sec) and fast (6 deg/sec) conditions. FSIQ = full-scale IQ. Final models are highlighted in boldface. Only variables retained in each step of the model are provided. * $p < .05$, ** $p <.01$.

[a] $R^2 = .45$, $p < .01$ for Step 1, $\Delta R^2 < -.01$, $p = .66$ for Step 2, $\Delta R^2 = -.01$, $p = .60$ for Step 3; [b] $R^2 = .54$, $p < .01$ for Step 1, $\Delta R^2 < .01$, $p = .95$ for Step 2, $\Delta R^2 < .01$, $p = .94$ for Step 3; [c] $R^2 = .26$, $p = .07$ for Step 1, $\Delta R^2 < .01$, $p = .89$ for Step 2, $\Delta R^2 = <-.01$, $p = .69$ for Step 3, $\Delta R^2 = -.02$, $p = .43$ for Step 4; [d] $R^2 = .38$, $p < .01$ for Step 1, $\Delta R^2 = -.02$, $p = .35$ for Step 2, $\Delta R^2 = -.05$, $p = .13$ for Step 3.

Table 5.4 Bivariate correlations between psychophysical measures and other measures.

	Children with autism																*Typically developing children*									
Psychophysical measure	*Age*		*VIQ*		*PIQ*		*FSIQ*		*SCQ*		*ADOS SA*		*ADOS RRB*		*ADOS Total*		*Age*		*VIQ*		*PIQ*		*FSIQ*		*SCQ*	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
No-noise threshold																										
1.5 deg/sec	-.43 ^{a}	.01	<.01 ^{a}	.99	**-.45 ^{a}**	**<.01**	-.32 ^{a}	.07	.26 ^{b}	.15	-.19 ^{c}	.30	-.12 ^{c}	.52	-.20 ^{c}	.28	-.34 ^{a}	.06	-.33 ^{a}	.06	.04 ^{a}	.82	-.17 ^{a}	.34	.15 ^{d}	.46
6 deg/sec	**-.45 ^{a}**	**<.01**	.13 ^{a}	.47	-.25 ^{a}	.17	-.12 ^{a}	.52	.39 ^{b}	.03	-.36 ^{c}	.04	-.22 ^{c}	.23	-.37 ^{c}	.04	**-.46 ^{a}**	**<.01**	-.24 ^{a}	.17	-.30 ^{a}	.09	-.33 ^{a}	.06	.38 ^{d}	.05
MTN																										
1.5 deg/sec	.28 ^{a}	.12	-.21 ^{a}	.23	.08 ^{a}	.68	-.04 ^{a}	.84	-.01 ^{b}	.96	.35 ^{c}	.05	.18 ^{c}	.32	.35 ^{c}	.05	.18 ^{a}	.31	.15 ^{a}	.41	-.12 ^{a}	.52	<-.01 ^{a}	.99	-.04 ^{d}	.85
6 deg/sec	.05 ^{a}	.77	<.01 ^{a}	.99	.25 ^{a}	.17	.17 ^{a}	.35	-.08 ^{b}	.66	.18 ^{c}	.33	.23 ^{c}	.20	.22 ^{c}	.23	.03 ^{a}	.88	.33 ^{a}	.06	.03 ^{a}	.86	.21 ^{a}	.23	-.19 ^{d}	.33
Internal noise																										
1.5 deg/sec	-.32 ^{a}	.07	-.14 ^{a}	.45	**-.45 ^{a}**	**<.01**	-.38 ^{a}	.03	.32 ^{b}	.08	-.01 ^{c}	.95	-.02 ^{c}	.94	-.01 ^{c}	.94	-.22 ^{a}	.23	-.21 ^{a}	.25	-.06 ^{a}	.73	-.17 ^{a}	.33	.10 ^{d}	.60
6 deg/sec	-.38 ^{a}	.03	.10 ^{a}	.58	-.11 ^{a}	.55	-.04 ^{a}	.84	.34 ^{b}	.06	-.23 ^{c}	.20	-.09 ^{c}	.62	-.23 ^{c}	.22	-.40 ^{a}	.02	-.02 ^{a}	.92	-.23 ^{a}	.19	-.16 ^{a}	.39	.22 ^{d}	.26
Sampling																										
1.5 deg/sec	.30 ^{a}	.10	-.23 ^{a}	.20	.12 ^{a}	.53	-.02 ^{a}	.92	.03 ^{b}	.89	.34 ^{c}	.06	.20 ^{c}	.26	.35 ^{c}	.05	.10 ^{a}	.58	.10 ^{a}	.57	-.16 ^{a}	.38	-.06 ^{a}	.75	-.04 ^{d}	.86
6 deg/sec	.04 ^{a}	.84	.02 ^{a}	.92	.25 ^{a}	.17	.18 ^{a}	.33	-.06 ^{b}	.73	.20 ^{c}	.28	.20 ^{c}	.28	.22 ^{c}	.22	.08 ^{a}	.66	.31 ^{a}	.08	.07 ^{a}	.71	.22 ^{a}	.22	-.22 ^{d}	.25
Motion coherence																										
1.5 deg/sec	-.25 ^{c}	.17	-.06 ^{c}	.74	-.31 ^{c}	.09	-.25 ^{c}	.17	.20 ^{e}	.29	-.13 ^{b}	.48	-.14 ^{b}	.47	-.15 ^{b}	.42	**-.49 ^{a}**	**<.01**	.06 ^{a}	.75	-.26 ^{a}	.15	-.11 ^{a}	.53	.30 ^{d}	.12
6 deg/sec	-.14 ^{c}	.46	.12 ^{c}	.51	-.31 ^{c}	.09	-.15 ^{c}	.41	.19 ^{e}	.31	-.17 ^{b}	.37	-.24 ^{b}	.19	-.21 ^{b}	.25	**-.45 ^{a}**	**<.01**	-.21 ^{a}	.25	-.30 ^{a}	.09	-.31 ^{a}	.08	.33 ^{d}	.09

Note. Bivariate correlations between psychophysical measures in the equivalent noise and motion coherence tasks, and age, Verbal IQ (VIQ), Performance IQ (PIQ) and Full-scale IQ (FSIQ) and Social Communication Questionnaire (SCQ; Rutter et al., 2003) scores for children with autism and typically developing children. Correlations with social affect (SA), restricted and repetitive behaviour (RRB) and total scores of the Autism Diagnostic Observation Schedule (ADOS; Lord et al., 1999, 2012) are shown for children with autism only. A conservative significance level of $p < .01$ was adopted for all correlations. Significant correlations are highlighted in boldface.

^{a} *df* = 31, ^{b} *df* = 29, ^{c} *df* = 30, ^{d} *df* = 26, ^{e} *df* = 28

Table 5.5 Partial correlations between thresholds and other variables

	Children with autism								*Typically developing children*	
Psychophysical measure	*SCQ*		*ADOS SA*		*ADOS RRB*		*ADOS Total*		*SCQ*	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
No-noise threshold										
1.5 deg/sec	.20 [b]	.31	-.29 [c]	.13	-.16 [c]	.39	-.29 [c]	.12	-.03 [d]	.90
6 deg/sec	.42 [b]	.03	-.43 [c]	.02	-.24 [c]	.21	-.44 [c]	.02	.13 [d]	.52
MTN										
1.5 deg/sec	-.03 [b]	.90	.36 [c]	.05	.17 [c]	.36	.36 [c]	.05	.04 [d]	.87
6 deg/sec	-.05 [b]	.82	.21 [c]	.27	.26 [c]	.17	.25 [c]	.18	-.14 [d]	.49
Internal noise										
1.5 deg/sec	.24 [b]	.21	-.09 [c]	.64	-.06 [c]	.76	-.09 [c]	.63	-.03 [d]	.89
6 deg/sec	..37 [b]	.05	-.27 [c]	.15	-.08 [c]	.68	-.26 [c]	.17	.03 [d]	.89
Sampling										
1.5 deg/sec	.02 [b]	.91	.36 [c]	.05	.20 [c]	.30	.36 [c]	.05	-.02 [d]	.94
6 deg/sec	-.02 [b]	.92	.23 [c]	.23	.22 [c]	.23	.26 [c]	.17	-.15 [d]	.47
Motion coherence										
1.5 deg/sec	.15 [e]	.44	-.21 [b]	.27	-.19 [b]	.32	-.24 [b]	.22	.19 [d]	.37
6 deg/sec	.16 [e]	.42	-.22 [b]	.26	-.28 [b]	.14	-.27 [b]	.16	.08 [d]	.71

Note. Correlations between psychophysical measures in the equivalent noise and motion coherence tasks, and Social Communication Questionnaire (SCQ; Rutter et al., 2003) scores and Autism Diagnostic Observation Schedule (ADOS; Lord et al., 1999, 2012) scores once controlling for age and full-scale IQ. SA = social affect; RRB = restricted and repetitive behaviour. N.b. ADOS scores were not obtained for typically developing children. A conservative significance level of $p < .01$ was adopted for all correlations.
[a] *df* = 29, [b] *df* = 27, [c] *df* = 28, [d] *df* = 24, [e] *df* = 26.

5.3.8 Relationships with other variables

5.3.8.1 Relationships with age and ability.

Next I investigated how task performance related to general developmental variables (age and ability) in the children with autism and TD children. A conservative significance level of $p < .01$ was adopted to account for multiple correlations. As shown in Table 5.4, no-noise thresholds were negatively related to age in the fast speed condition for children with autism and TD children (*p*s < .01), with older children having lower thresholds. In the slow condition, age was marginally related to no-noise thresholds in the children with autism ($p = .01$), but not in TD children ($p = .06$). No-noise thresholds in the slow condition were negatively related to PIQ scores in the children with autism ($p < .01$), with lower thresholds being associated with higher PIQ scores. Similarly, internal noise in the slow condition was negatively related to PIQ in children with autism ($p < .01$). Consistent with the regression analyses presented above, motion coherence thresholds significantly reduced with age in the TD group, for both speed conditions (*p*s < .01), but this relationship was not significant in the autism group (*p*s ≥ .17). All other correlations between psychophysical performance and age and IQ measures were non-significant (all *p*s ≥ .02, see Table 5.4).

5.3.8.2 Relationships with autism symptoms.

Due to a proposed relationship between severity of autistic symptoms and sensory atypicalities (see Section 1.2), I investigated relationships between psychophysical measures and scores on the SCQ and ADOS. No relationships between psychophysical measures and SCQ scores or ADOS scores were significant, using a conservative significance level of $p < .01$ (all *p*s ≥ .03, see Table 5.4). This pattern was consistent when controlling for age and FSIQ (all *p*s ≥ .02, Table 5.5).

5.3.9 Fixation results

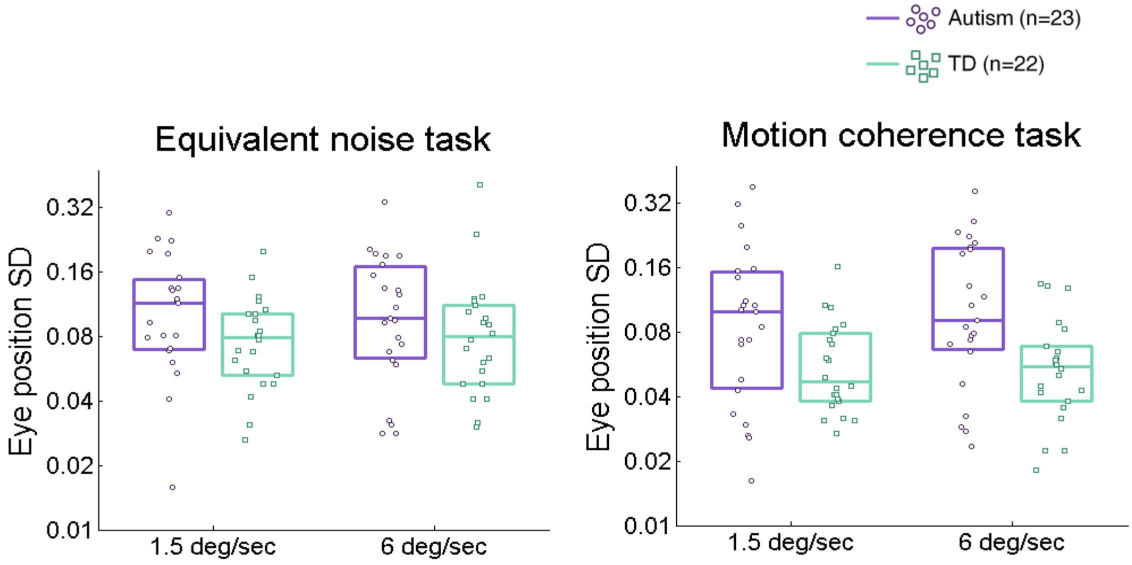

Figure 5.5 Fixation standard deviations

Standard deviations of fixations in the equivalent noise task (left panel) and the motion coherence task (right panel), for children with autism (purple circles) and typically developing children (TD; green squares). Lower values reflect greater fixation stability. Box plots represent median values and interquartile ranges for each group.

Finally, I investigated whether group differences in motion processing could be attributed to differences in the ability to maintain fixation. Fixation data was collected for a subset of 23 children with autism and 22 TD children (see Section 5.2.4). These groups did not differ in age, $t(43) = .85$, $p = .40$, VIQ, $t(43) = 1.16$, $p = .25$, PIQ, $t(43) = .34$, $p = .74$ or FSIQ, $t(43) = .41$, $p = .68$.

Fixation standard deviations were entered into a mixed design ANOVA, with task (equivalent noise, motion coherence) and speed condition (slow: 1.5 deg/sec, fast: 6 deg/sec) as within-participants factors, group as a between-participants factor, and age and FSIQ as covariates. A preliminary ANOVA on standard deviations in the equivalent noise task revealed no main effect of noise condition (no-noise, high-noise) and no interactions with group or speed condition ($ps \geq .14$), and so this factor was not analysed further.

The within-subjects effects of task and speed condition were initially tested in the absence of covariates. As shown in Figure 5.5, higher fixation standard deviations were found in the equivalent noise task (*M* = -1.06, *SD* = .27) than the motion coherence task (*M* = -1.16, *SD* = .32), *F*(1, 43) = 12.79, *p* < .01, η_p^2 = .23. The effect of speed condition, however, was not significant, *F*(1, 43) = .64, *p* = .43. Both covariates had significant effects on fixation standard deviations (age: *F*[1, 41] = 5.44, *p* = .03, η_p^2 = .12; FSIQ: *F*[1, 41] = 6.19, *p* = .02, η_p^2 = .13), with older children and those with higher FSIQ scores having lower fixation standard deviations. Neither covariate interacted with task or speed condition, *p*s ≥ .08.

Children with autism had higher fixation standard deviations (*M* = -1.02, *SD* = .32) than TD children (*M* = -1.20, *SD* = .24), *F*(1, 41) = 7.06, *p* = .01, η_p^2 = .15, and there was a significant interaction between group and task, *F*(1, 41) = 5.52, *p* = .02, η_p^2 = .12. *Post hoc* ANOVAs on each task separately revealed a significant group difference for the motion coherence task only, *F*(1, 41) = 9.74, *p* < .01, η_p^2 = .19, and not the equivalent noise task, *F*(1, 41) = 2.92, *p* = .10. No other interactions were significant, *p*s ≥ .13.

Importantly, however, fixation standard deviations were not related to no-noise thresholds, MTN, internal noise, sampling or motion coherence threshold estimates in either speed condition, in either group (all *p*s ≥ .13), and this pattern was consistent when controlling for age and FSIQ (all *p*s ≥ .06). It is of particular note that no relationships were found between fixation stability and internal noise estimates, in contrast to those reported in Chapter 4.

5.4 Discussion

In this study, an equivalent noise direction integration task was presented alongside a standard motion coherence task to children with autism and TD children aged 6 to 13 years to investigate whether local and/or global processing limits direction processing in children with autism. When there was no directional noise in the stimulus (i.e., when all dots moved in the same direction), children with autism were just as sensitive to directional offsets as TD children. Surprisingly, however, children with autism were able to compute the average dot direction over a *greater* amount of directional noise (variability) than TD children. Equivalent noise modelling suggested that children with autism have typical levels of internal noise, and can globally pool over *more* local elements to make their judgements compared to TD children. In contrast to the findings reported in Chapter 2, children with autism had comparable motion coherence thresholds to TD children.

I hypothesised that children with autism would show *reduced* integration of motion signals compared to TD children, in line with previous interpretations of elevated motion coherence thresholds in autism (e.g., Pellicano et al., 2005; see also Sections 1.6.2 and 2.4). These results therefore directly oppose the hypothesis, as children with autism were able to tolerate *more* directional variability than TD children when computing the average direction of stimulus elements. Indeed, a comparison of the performance of the child groups with that of the adults from Chapter 4 showed that children with autism were adult-like in their integration abilities. While inconsistent with previous conceptualisations of local and global processing in autism (e.g., Weak Central Coherence [WCC]; Frith & Happé, 1994), this finding is potentially consistent with a cognitive account of increased perceptual capacity in autism (Remington, Swettenham, Campbell, & Coleman, 2009; Remington, Swettenham, & Lavie, 2012). Perceptual capacity increases with age in TD children (Remington, Cartwright-Finch, & Lavie, 2014), which fits with the suggestion that children with autism may be more mature in their responses. A possible neural mechanism underlying an increased capacity for processing motion information is the presence of larger extrastriate population receptive fields in individuals with autism (Schwarzkopf, Anderson, de Haas, White, & Rees, 2014). However, the size of extrastriate population receptive fields has so far only been measured in adults with autism.

Equivalent noise analysis allowed me to quantify the extent to which internal noise and/or global sampling limits direction integration performance in children with and without autism. The results suggest that children with autism have typical levels of internal noise, but can effectively sample over *more* dots to make their judgments than TD children. As noted in Section 4.4, increased sampling can be thought of as reduced multiplicative noise being added to all estimates in the pooling process (i.e., reduced 'global noise'; Dakin et al., 2005). Irrespectively, increased sampling should confer an advantage at all levels of directional noise (Dakin et al., 2005). Yet, children with autism performed similarly to TD children in the no-noise condition. A trend towards increased internal noise in the children with autism might, to some extent, be counteracting the benefit of increased sampling in the no-noise condition.

It is also possible that children with autism might not use the same averaging strategy in the no-noise condition that leads to benefits in the high-noise condition (Allard & Cavanagh, 2012). A similar pattern of equivalent noise function, with specific enhancements at high but not low levels of external noise, has been demonstrated using other related paradigms (Dosher & Lu, 2000; Lu & Dosher, 1998). For example, attention can facilitate orientation discrimination performance in the presence of irrelevant contrast noise by allowing the observer effectively to exclude external noise and focus their perceptual analysis on the orientation signal (termed perceptual template re-tuning; Dosher & Lu, 2000; Lu & Dosher, 1998). However, unlike in previous work, here external noise was imposed on the relevant stimulus dimension (i.e., direction) and, hence, there was no noise to *exclude* as such. Yet it is possible that a similar mechanism of perceptual template re-tuning may explain why the thresholds of children with autism are less influenced by external noise. In this paradigm, optimal performance constitutes averaging all information. Children with autism may be able to focus on informative characteristics of the stimulus more effectively (and thus more optimally) compared to TD children, who may be integrating over an inappropriately narrow range of directions.

Another possibility is that group differences arise from differences in feature-tracking strategies (Cavanagh, 1992; Lu & Sperling, 1995, 1996, 2001), given that both stimulus speeds fall within the limit for attentive tracking (Verstraten, Cavanagh, & Labianca, 2000). A feature-tracking strategy would potentially be detrimental under conditions of high directional variability. If children with autism rely to a lesser extent on such a strategy, they may show enhanced performance specifically in the presence of directional variability. This account remains speculative, however, and requires validation with stimuli specifically designed to probe the third-order or attentional motion system.

It is clear that further research is required to understand the pattern of performance displayed by children with autism in the equivalent noise task. However, the current results do not provide strong support for either increased (e.g., Simmons et al., 2009) or reduced (G. Davis & Plaisted-Grant, in press; Greenaway et al., 2013) neural noise in autism (apart from within the context of reduced global noise, as suggested above). Nevertheless, support for increased noise in autism has been provided by reports of increased trial-by-trial variability in electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) recordings (Dinstein et al., 2012; Milne, 2011). It is not yet clear how such physiological measures of variability relate to psychophysical measures like those reported in the current study. However, it is unlikely to be a simple relationship, as noise can arise from many different sources (Faisal et al., 2008), and may potentially have different effects in different brain areas. The internal noise estimate reported here specifically reflects local noise limiting direction integration, which is likely to be operating at the level of direction-selective cells in V1. Indeed, it is possible that individuals with autism have atypical levels of neural noise in brain regions involved in other visual processing tasks.

Regression analyses were conducted to determine what limits motion coherence sensitivity in children with autism. Both sampling and internal noise predicted motion coherence sensitivity in children with autism, for both slow and fast speed conditions. These results contrast the findings from typical development reported in Chapter 4, which showed that only sampling, and not internal noise, predicted the development of motion coherence thresholds. Furthermore, no relationship was found between sampling and motion coherence sensitivity in the TD group of the current study: instead motion coherence sensitivity was only predicted by age (and FSIQ in the fast condition). The fact that sampling did not predict motion coherence thresholds in TD children in the current study may be indicative of a lack of statistical power. Interestingly, however, the results in the current study suggest that the mechanisms underlying the development of motion coherence sensitivity may differ between children with autism and TD children. Age was a significant predictor of motion coherence sensitivity only in the TD group, which also suggests that motion coherence sensitivity may develop differently in children with autism. However, more statistical power is necessary to fully distinguish between the developmental trajectories in the two groups.

Given that increased sampling was related to increased motion coherence sensitivity in children with autism, it is important to consider why the children with autism were not also more sensitive to coherent motion information compared to TD children. Another factor must be involved that prevents the translation of increased sampling into increased motion coherence sensitivity in the autism group. In the equivalent noise direction integration task, all dots are ‘signal’ dots, and therefore the optimal strategy is to average as many dots as possible. However, in the motion coherence task, ‘signal’ dots are interspersed with ‘noise’ dots, and arguably the optimal strategy is to segregate the signal dots from noise dots in order to perform the task. It is therefore possible that children with autism are less able, or less inclined, to use segregation strategies compared to TD children, meaning that they do not show enhanced sensitivity in motion coherence tasks despite an ability to globally average more dots. Correspondingly, Plaisted (2001) suggested that individuals with autism do not filter out irrelevant features to the same extent as TD individuals, as they perceive these local features as highly discriminable, salient features – an idea that is also reflected in G. Davis and Plaisted-Grant’s (in press) account of reduced noise in autism. It has also been suggested that reduced segregation of signal from noise (or ‘noise exclusion’) may limit motion coherence sensitivity in other conditions, such as dyslexia (Sperling, Lu, Manis, & Seidenberg, 2005, 2006) and migraine (Tibber et al., 2014; Webster et al., 2011).

A pattern of increased integration and reduced segregation abilities may potentially be accounted for within a Bayesian framework. Pellicano and Burr (2012) proposed that children with autism might have weak priors, leading to an overreliance on incoming sensory information. According to this account, it is possible that children with autism sample more motion signals than TD children as they are not using accumulated knowledge about what is relevant and irrelevant in the world in order to filter certain information out.

In the current study, children with autism had comparable motion coherence thresholds to TD children, which contrasts previous findings, including those reported in Chapter 2. Indeed, there is a lot of variability between children with autism (and TD children), and perhaps the discrepant results simply reflect cohort differences. However, there are at least six differences in task and stimulus parameters between the current motion coherence task and the motion coherence task presented in Chapter 2. First, in Chapter 2, two stimuli were presented sequentially with an ISI of 500 ms, whereas in this study a single stimulus was presented. While it could be argued that sequential presentation introduces working memory demands that pose particular challenges for children with autism, sequential presentation did not appear to limit the performance of children with autism in the speed discrimination task or the fast condition of the motion coherence task in Chapter 2. Furthermore, Chen et al. (2012) suggested that adolescents with autism may even show *enhanced* sensitivity to speed information over a long ISI. The sequential presentation therefore does not appear to explain the discrepant results.

Second, whereas the current task asked children to discriminate the direction of coherent motion, the task in Chapter 2 asked children to *detect* coherent motion. It is not apparent why detection would be disproportionately more difficult for children with autism than discrimination, and indeed, overall lower thresholds were obtained in Chapter 2 than in the current study. Third, the stimuli presented in the current study were shorter (400 ms) than the stimuli presented in Chapter 2 (1000 ms). However, C. E. Robertson et al. (2012) reported elevated thresholds only for short (200 ms) and not long (400 ms, 1500 ms) stimulus durations. C. E. Robertson et al. suggested that individuals with autism require a longer temporal integration window for processing coherent motion, and therefore difficulties should be more pronounced for shorter durations. The difference in durations therefore does not appear to explain the discrepant results.

Fourth, in the current study, white dots were presented on a grey background whereas in Chapter 2, white dots were presented on a black background. While this contrast difference may potentially be an important stimulus parameter, it is currently unclear why it would have a disproportionate effect on motion coherence thresholds for children with autism. Fifth, the density of dots was slightly lower in the current study (0.57 dots/deg^2) than in Chapter 2 (0.83 dots/deg^2). It has previously been demonstrated that dot density affects the motion coherence thresholds of children, with elevated thresholds being obtained under conditions of low dot density (Narasimhan & Giaschi, 2012). Yet, it is not clear why children with autism would show elevated thresholds specifically for the more dense stimuli presented in Chapter 2.

The final difference – and perhaps the difference that offers the most parsimonious explanation of the discrepant results – is that the tasks differed in the lifetime of dots. While limited lifetime stimuli are intended to prevent tracking strategies, short lifetimes also introduce correspondence noise (i.e., false correspondences between dot pairs on successive frames; Barlow & Tripathy, 1997), which might contribute to motion processing difficulties in children with autism (Simmons et al., 2009). Indeed, it has been recognised previously that correspondence noise has a detrimental effect on motion segregation (Watamaniuk, Flinn, & Stohr, 2003), hence atypical segregation abilities in autism may be more pronounced when using limited lifetime stimuli. In support of this suggestion, Jackson et al. (2013) found that the motion coherence performance of adults with high levels of autistic traits was more disrupted by limited lifetime stimuli than those with low levels of autistic traits. However, it remains to be investigated whether this finding generalises to children who have a diagnosis of autism. I test the possibility that limited lifetime is particularly disruptive for children with autism compared to TD children in Chapter 6.

In Chapter 2, elevated motion coherence thresholds were found only at a slow stimulus speed (1.5 deg/sec) and not a fast stimulus speed (6 deg/sec). Therefore, in the current study, motion coherence and equivalent noise tasks were presented at both stimulus speeds. In the current study, no interactions were found between speed condition and group in estimates of internal noise, sampling or motion coherence. It is possible that the elevated motion coherence thresholds reported in Chapter 2 reflect specific difficulties in dealing with correspondence noise at slow speeds for children with autism. As the limited lifetime was kept constant across speed conditions, each dot moved a shorter distance before decaying in the slow condition than in the fast condition, meaning that the motion signal was weaker, and potentially more susceptible to correspondence noise.

As reviewed in Section 1.2, atypical perception may be related to the extent of autistic symptomatology. I therefore investigated relationships between psychophysical measures and measures of autistic symptoms (SCQ and ADOS scores). No relationships were significant once controlling for age and FSIQ, which suggests that differences in performance, such as those in sampling, may reflect state differences (i.e., whether a child has autism or not) rather than trait differences. Alternatively, it is possible that the measures of autistic symptomatology used were not sensitive enough to detect such relationships.

Fixation data were collected in a subset of children with autism and TD children in order to investigate whether differences in motion processing reflected differences in the ability to maintain fixation. While children with autism had less stable fixations than the TD children in the motion coherence task, fixation stability was not related to any psychophysical measure. In particular, fixation stability was not related to internal noise as reported in the TD sample in Chapter 4. The relationship between internal noise and fixation stability therefore warrants further investigation. In the current study, participants were asked to fixate centrally during the task. It is an open question as to whether fixation behaviour might be related to motion processing performance in children with autism when they are allowed to view the stimuli freely.

In sum, two important implications emerge from this study. First, the findings challenge the common assumption that children with autism have difficulties with global motion integration and instead suggest that children with autism integrate *more* efficiently than TD children. Second, the results suggest that previously reported difficulties in motion coherence tasks may be due to difficulties segregating signal from noise in individuals with autism rather than reduced global integration. The fact that elevated motion coherence thresholds were not found in the current study suggests that such difficulties may be dependent on specific stimulus parameters such as dot lifetime. These findings therefore call for a more nuanced account of motion processing abilities in children with autism.

6 The effect of dot lifetime on motion coherence thresholds in children with autism

6.1 Introduction

In Chapter 2, I reported elevated motion coherence thresholds in children with autism compared to typically developing (TD) children for slow-moving (1.5 deg/sec), but not fast-moving (6 deg/sec), stimuli. Conversely, in Chapter 5, I reported that children with autism had comparable motion coherence thresholds as TD children for both stimulus speeds. In Section 5.4 I suggested that these discrepant results might be due to participant differences and/or differences in task and stimulus parameters. In particular, I highlighted six ways that the stimuli and task requirements differed between Chapter 2 and Chapter 5: (1) sequential stimulus presentation versus single stimulus presentation, (2) detection of coherent motion versus direction discrimination, (3) long (1000 ms) versus short (400 ms) stimulus duration, (4) black background versus grey background, (5) higher (0.83 dots/deg^2) versus lower (0.57 dots/deg^2) dot density, and (6) limited lifetime versus unlimited lifetime dots.

I suggested that dot lifetime was the most critical difference between the tasks, as it has been shown that limiting dot lifetime leads to elevated motion coherence thresholds in TD adults (Braddick et al., 1998; Festa & Welch, 1997; Hiris & Blake, 1995; Jackson et al., 2013). It has been suggested that limited lifetime might lead to elevated thresholds because it a) prevents the ability to track individual dots (e.g., Jackson et al., 2013), b) introduces correspondence noise (Barlow & Tripathy, 1997), c) reduces the strength of activations within short-range filters (Pilly & Seitz, 2009; Watamaniuk et al., 2003), d) increases the need for temporal integration (Festa &

Welch, 1997), and e) interferes with temporal smoothness (Lee & Lu, 2010; Watamaniuk et al., 2003).

Simmons et al. (2009) suggested that correspondence noise might present particular difficulties for individuals with autism. Preliminary support for this hypothesis has been provided by Jackson et al. (2013) who compared the motion coherence thresholds of adults in the general population with varying levels of autistic traits, measured by the autism-spectrum quotient (AQ; Baron-Cohen et al., 2001). The performance of individuals with high levels of autistic traits (i.e., high AQ-scorers) was *more* disrupted by the introduction of limited lifetime than that of low AQ-scorers, and high AQ-scorers showed *enhanced* sensitivity to coherent motion in the unlimited lifetime condition compared to low AQ-scorers. It is conceivable that limited lifetime might have a particularly disruptive effect at slow speeds (where each dot travels only a short distance before it decays), which may explain why elevated motion coherence thresholds in children with autism were found only in the slow (1.5 deg/sec) condition in Chapter 2.

This study directly tested the possibility that limited lifetime has a disproportionate effect on the motion coherence thresholds of children with autism compared to those of TD children. The motion coherence task presented in Chapter 2 was given to children with autism aged 7 to 13 years and TD children matched in age and non-verbal ability, with two stimulus conditions: limited lifetime and unlimited lifetime. All stimuli moved at 1.5 deg/sec, because elevated motion coherence thresholds were found only for this slow stimulus speed (and not for a fast stimulus speed of 6 deg/sec) in Chapter 2.

6.2 Methods

6.2.1 Participants

Thirty-eight children with autism and 81 TD children were recruited for the current study[9]. Children with autism who had participated in the previous study (Chapter 5) were invited to take part in this follow-up study, and additional children with autism were recruited through community contacts. TD children were primarily recruited through a primary school in Hertfordshire and a public engagement event held at the Institute of Education. Four children with autism were removed from the dataset as their IQ scores indicated intellectual impairment (verbal IQ [VIQ] < 70 and/or performance IQ [PIQ] < 70) as assessed by the Wechsler Abbreviated Scales of Intelligence (WASI or WASI-II; Wechsler, 1999, 2011; see Section 5.2.2).

Parents completed the Social Communication Questionnaire (SCQ; Rutter et al., 2003; see Section 2.2.3) and children with autism were administered the Autism Diagnostic Observation Schedule (ADOS-G or ADOS-2; Lord et al., 1999, 2012; see Section 5.2.2)[10]. As in previous chapters, only those who scored above threshold for an autism spectrum condition on at least one of these measures were included in the dataset. One child with autism was removed from the dataset as he did not meet the autism spectrum cut-off on either measure. One child with autism obtained poorly-fitting psychometric functions in the task and was therefore removed from analysis (Section 2.2.7). Two TD children were removed from the dataset due to parent-reported

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[9] Due to time restrictions for testing in school, 8 TD children were not administered the full experimental procedure. These children were given short versions of the experimental tasks, only, and were therefore not included in the final dataset.

[10] ADOS scores could not be obtained for one child with autism who was selectively mute, and revised algorithm scores could not be computed for one child with autism who had recently been diagnosed using the ADOS-G (as noted in Section 5.2.2).

diagnoses of developmental conditions (global developmental delay and dyspraxia). All remaining TD children scored below the cut-off for autism on the SCQ (Rutter et al., 2003). A Snellen acuity chart was used to confirm normal or corrected-to-normal visual acuity, using optical corrections where necessary. Normal acuity was defined as a binocular acuity of 6/9 or better for children aged 7 to 8 years and 6/6 or better for older children. One TD child and one child with autism were removed from the dataset as they did not meet this criterion.

Thirty-one children with autism (*M* = 10 years; 11 months, range 7;3 – 13;6, 2 females) were therefore included in the final dataset. Thirty-one TD children (*M* = 10 years; 9 months, range 7;9 - 13;10, 10 females) were selected to match the children with autism on an individual basis. The resulting groups did not differ in terms of chronological age, $t(60) = .39$, $p = .70$, PIQ, $t(60) = 1.26$, $p = .21$, or full-scale IQ (FSIQ), $t(60) = 1.16$, $p = .25$. However, the children with autism had lower VIQ scores than the TD children (see Table 6.1), $t(60) = 3.85$, $p < .01$. Participant demographics of children included in the final dataset are provided in Table 6.1.

Twenty-eight children with autism had previously participated in the study reported in Chapter 5, and of these, nine had also participated in Chapter 2. Four TD children had participated in the study reported in Chapter 2, and 13 TD children had taken part in the studies reported in Chapters 4 and 5 (including one TD child who had also participated in Chapter 2)[11]. Ten participants with autism had additional diagnoses of developmental conditions, as reported by parents. Seven children with autism had diagnoses of attention deficit/hyperactivity disorder (AD/HD), with three of these also

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[11] Nine children with autism and one TD child therefore had previous experience of the motion coherence task. However, the study reported in Chapter 2 was conducted approximately 2 years prior to the current study, making the transfer of practice effects to the new study unlikely.

reported to have one or more additional conditions (including tic disorders, dyslexia, dyspraxia and auditory processing disorder). Three participants with autism had diagnoses of dyslexia, sensory processing disorder and dyspraxia, respectively, without a co-occurring diagnosis of AD/HD.

Table 6.1 Participant characteristics

Measures	*Children with autism*	*Typically developing children*
N	31	31
Gender (*n* males: *n* females)	29:2	21:10
Age (years;months)		
Mean (SD)	10;11 (1;11)	10;9 (1;10)
Range	7;3 – 13;6	7;9 – 13;10
Verbal IQ		
Mean (SD)	98.68 (9.54)	108.00 (9.53)
Range	81 – 120	91 – 130
Performance IQ		
Mean (SD)	106.87 (13.41)	102.55 (13.68)
Range	83 – 137	78 – 131
Full-scale IQ		
Mean (SD)	103.03 (10.99)	106.06 (9.58)
Range	83 – 127	89 – 124
Mother’s age on leaving full-time education (years)		
Mean (SD)	21.67 (3.16)	20.50 (3.22)
Range	16 – 30	15 – 26
SCQ score		
Mean (SD)	24.47 (7.43)	3.14 (3.10)
Range	5 – 38	0 – 14
ADOS social affect		
Mean (SD)	9.43 (4.58)	
Range	1 – 17	
ADOS restricted and repetitive behaviour		
Mean (SD)	2.04 (1.57)	
Range	0 – 6	
ADOS total score		
Mean (SD)	10.89 (5.44)	
Range	2 – 20	

Note. SCQ = Social Communication Questionnaire (Rutter et al., 2003); ADOS = Autism Diagnostic Observation Schedule (Lord et al., 1999, 2012).

Background questionnaires and SCQ forms (Section 2.2.2) were returned by 30 of the parents of children with autism and 28 of the parents of TD children included in the final dataset. The majority of parents reported being White British, both in the autism group (*n* = 25) and TD group (*n* = 15). Other ethnic backgrounds reported in the autism group were Latin American (*n* = 1), Indian (*n* = 2) and White American French

(n = 1), and in the TD group, White Irish (n = 1), Indian (n = 1), Bangladeshi (n = 1), South American (n = 2), Mixed White and Black African (n = 1), Mixed White Asian (n = 1), other Black backgrounds (n = 2) and other White backgrounds (n = 3). One parent of a child with autism and one parent of a TD child did not disclose their ethnic backgrounds. The mother's age on leaving full-time education did not differ between the groups, $t(54) = 1.37$, $p = .18$ (see Table 6.1 for group means).[12]

6.2.2 Apparatus and stimuli

In Chapter 2, stimuli were displayed on a CRT monitor. In this study, however, stimuli were displayed on a Dell Precision M4600 laptop as in Chapters 4 and 5, for the reasons outlined in Section 4.2.2. The stimuli were the same as in Chapter 2, and care was made to ensure that stimulus sizes were equated across the different screens. Stimuli consisted of 100 white dots displayed within either a red or blue aperture to the left or right of the central fixation point, respectively. The dots drifted for 1000 ms at a speed of 1.5 deg/sec. In the limited lifetime condition, each dot had a limited lifetime of 5 monitor refreshes (~83ms, as in Chapter 2). In the unlimited lifetime condition, each dot remained on the screen for the full duration of the stimulus (1000 ms), unless it drifted outside of the aperture, in which case it was randomly replaced within the aperture.

6.2.3 Procedure

Participants completed a motion coherence task in each of two dot lifetime conditions: limited lifetime and unlimited lifetime. The motion coherence task was the

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[12] Two parents of TD children did not report the mother's age on leaving full-time education.

same as that described in Section 2.2. A trial consisted of a pair of stimuli presented sequentially separated by a 500 ms interstimulus interval (ISI) in which the apertures and fixation point remained on the screen. A stimulus in the left (red) aperture was followed by a stimulus in the right (blue) aperture, and vice versa (Figure 6.1). The reference stimulus had 0% dot coherence whereas the comparison stimulus contained a percentage of coherently moving dots. Children were told that there were two species of firefly in ‘Insectland’: one with flashing lights (corresponding to the limited lifetime condition) and one with non-flashing lights (corresponding to the unlimited lifetime condition). As in Chapter 2, children were asked to work out which set of “fireflies” seemed to be “escaping” together in the same direction, and were told that they were competing against a “camera system” monitoring the boxes (Figure 2.3).

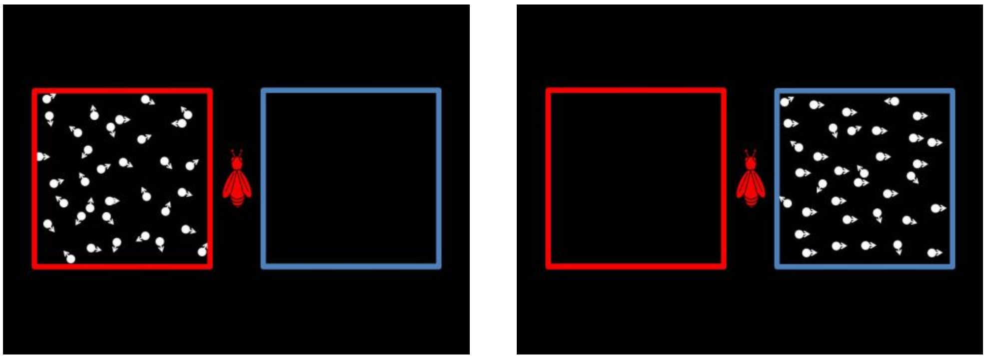
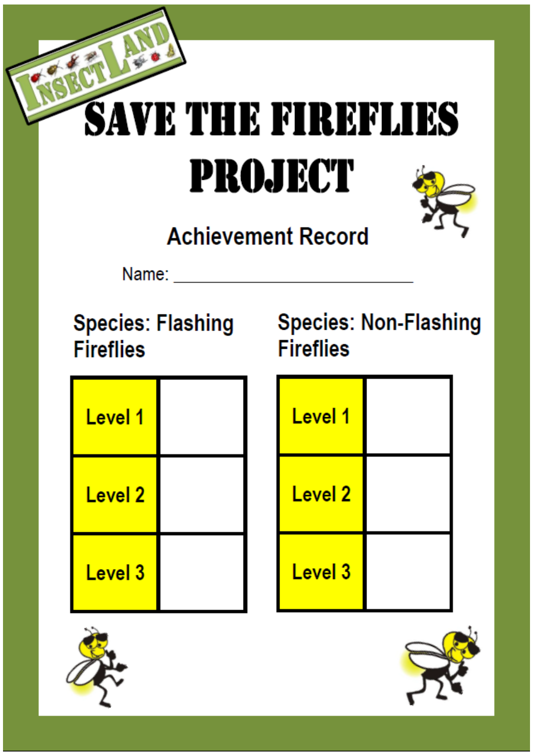


Figure 6.1 Schematic representation of stimuli

The left panel shows the reference stimulus in which dots move with 0% motion coherence, and the right panel shows the comparison stimulus which contains a proportion of coherently moving dots. Children were asked to select the stimulus that contained coherent motion. Arrows are for illustrative purposes only, representing the direction of dot motion.

As in previous chapters, each task condition was presented in the context of a game with three levels: a combined demonstration and criterion phase (“level 1”), a practice phase (“level 2”) and a threshold estimation phase (“level 3”). The experimental protocol was the same as in Chapter 2, apart from three minor changes. First, an extra four demonstration trials were presented to participants at a fast (6 deg/sec) stimulus speed to help familiarise children with the task, as some children exhibited difficulties in processing coherent motion in the slow condition in Chapter 2 (Section 2.2.7). Second, the simulated points shown to children after each block of trials were not fixed, but randomly jittered around a set of values, as in Chapters 4 and 5. Third, the record card given to children was updated to reflect the new experimental conditions (limited and unlimited lifetime; Figure 6.2).



INSECTLAND

SAVE THE FIREFLIES PROJECT

Achievement Record

Name: ______________________

Species: Flashing Fireflies

Level 1	
Level 2	
Level 3	

Species: Non-Flashing Fireflies

Level 1	
Level 2	
Level 3	

Figure 6.2 Record card

Record card for participants to mark their progress through the experimental session using a stamp. “Flashing fireflies” corresponds to the limited lifetime condition, and “non-flashing fireflies” corresponds to the unlimited lifetime condition.

6.2.4 General procedure

The procedure was approved by the Institute’s Faculty Research Ethics Committee. Parents gave their informed consent and children verbally assented. Children were tested in a dimly lit room and were seated 50 cm from the computer screen, which was fixed with a chin-rest. Both conditions (limited lifetime and unlimited lifetime) were presented to children in a single session lasting approximately 30 minutes. The order of presentation of conditions was counterbalanced between participants. If children had not taken part in a previous study, the WASI-II (Wechsler, 2011) and Snellen acuity test were completed in a further session. The ADOS-2 (Lord et al., 2012) was administered to children with autism who had not taken part previously.

6.2.5 Data screening and transformation

All participants included in the final dataset performed significantly above chance in the catch trials (i.e., responding correctly in 11 or more of the 16 catch trials). As described in Chapter 2, the percentage of incorrect responses to catch trials was used as an estimate of lapse rate for fitting psychometric functions (Treutwein, 1995). The data were bootstrapped and fit with a cumulative Gaussian function to obtain an estimate of the coherence level required for correct detection 75% of the time in log units. Outliers were identified as data-points with *z* scores of absolute values above 3. Screening revealed one outlying point in the unlimited lifetime condition belonging to a TD participant, which was retained but replaced with a threshold value corresponding to a *z* score of -2.5 (Tabachnick & Fidell, 2007). To minimise the effects of skewness and kurtosis, all of the analyses reported below were conducted with log values. However, motion coherence thresholds are displayed in linear units in Figure 6.3 to aid interpretability.

6.3 Results

6.3.1 Motion coherence thresholds

Initial analysis of variance (ANOVA) analysis confirmed that the order of conditions did not have a significant effect on motion coherence thresholds, $F(1, 58) =$

.08, *p* = .77, and did not interact with group or lifetime condition (*ps* ≥ .62). This factor was therefore removed from further analysis.

Examination of Figure 6.3 suggests that both children with autism and TD children were more sensitive to coherent motion in the unlimited lifetime condition than the limited lifetime condition. This within-participants effect was confirmed in a mixed design ANOVA on motion coherence thresholds, with group as a between-participants factor. As expected, higher motion coherence thresholds were obtained in the limited lifetime condition (*M* = -.72; *SD* = .23) than in the unlimited lifetime condition (*M* = -.81; *SD* = .19), *F*(1, 60) = 8.71, *p* < .01, η_p^2 = .13.

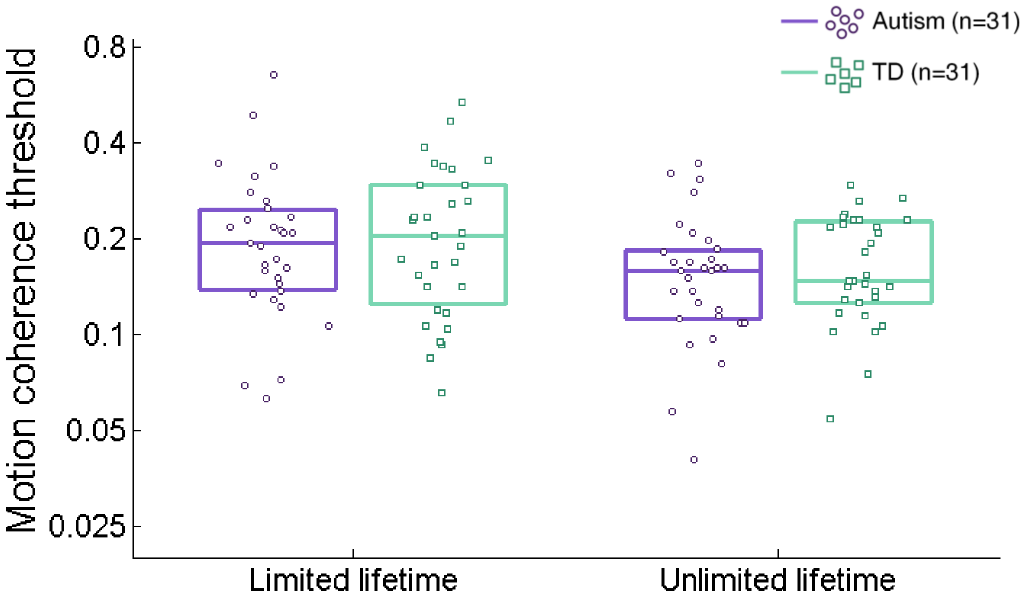


Figure 6.3 Motion coherence thresholds

The proportion of coherently moving dots required for accurate coherent motion detection for children with autism (purple circles) and typically developing children (TD; green squares) in limited lifetime and unlimited lifetime conditions. Box plots represent median values and interquartile ranges for each group. N.b. Data are presented with outliers replaced (Tabachnick & Fidell, 2007).

As in previous chapters, age and FSIQ were then added into the ANOVA as covariates. FSIQ had a significant effect on motion coherence thresholds, *F*(1, 58) = 7.06, *p* = .01, η_p^2 = .11, with higher FSIQ scores being associated with lower motion coherence thresholds. Age did not have a significant effect on motion coherence thresholds, *F*(1, 58) < .01, $p = .97$, and neither covariate interacted with lifetime condition, *p*s ≥ .42. Unexpectedly, the children with autism had similar motion coherence thresholds as the TD children, *F*(1, 58) = 1.00, $p = .32$, and there was no interaction between group and lifetime condition, *F*(1, 58) = .04, $p = .84$.

Finally, to investigate whether the participants who took part in Chapter 2 differed to those who had not taken part in Chapter 2, participation in Chapter 2 was added to the ANCOVA model as a between-participants factor (had taken part, had not taken part). Children who had taken part in Chapter 2 had similar motion coherence thresholds (*M* = -.78, *SD* = .24) as those who had not taken part (*M* = -.76, *SD* = .21), *F*(1, 56) = .17, $p = .68$. Furthermore, participation in Chapter 2 did not interact with group or lifetime condition, *p*s ≥ .20. The performance of those who had previously participated in Chapter 2 was therefore indistinguishable from those who had not, suggesting that previous experience with the task in Chapter 2 had no effect on motion coherence thresholds.

6.3.2 Relationships between thresholds and other variables

6.3.2.1 Relationships with age and ability.

Next I investigated whether motion coherence thresholds were related to general developmental variables (age and ability) in the children with autism and TD children. Bivariate correlations between motion coherence thresholds and age and IQ scores are provided in Table 6.2. When adopting a conservative significance level of $p < .01$, no relationships were significant.

6.3.2.2 Relationships with autism symptoms.

As in Chapter 2 and Chapter 5, I investigated whether task performance was related to autism symptomatology. In Chapter 2, motion coherence thresholds were not related to ADOS scores or SCQ scores once controlling for age and FSIQ. In this study there were similarly no relationships between SCQ scores or ADOS scores and thresholds in either lifetime condition, once controlling for age and FSIQ (*p*s ≥ .03, Table 6.2).

Table 6.2 Correlations between motion coherence thresholds and other measures

	Children with autism				*Typically developing children*			
	Limited lifetime		*Unlimited lifetime*		*Limited lifetime*		*Unlimited lifetime*	
Measure	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Bivariate correlations								
Age	-.30 [a]	.10	-.13 [a]	.48	.01 [a]	.96	.17 [a]	.36
VIQ	-.36 [a]	.05	-.20 [a]	.28	.03 [a]	.89	-.24 [a]	.20
PIQ	-.30 [a]	.10	-.03 [a]	.87	-.31 [a]	.09	-.23 [a]	.21
FSIQ	-.39 [a]	.03	-.14 [a]	.46	-.24 [a]	.20	-.33 [a]	.07
SCQ	.18 [b]	.34	.40 [b]	.03	.29 [c]	.14	.08 [c]	.67
ADOS								
Social affect	-.08 [d]	.69	.05 [d]	.79				
RRB	-.09 [d]	.65	-.24 [d]	.22				
Total	-.05 [d]	.80	-.05 [d]	.82				
Partial correlations (age, full-scale IQ)								
SCQ	.11 [c]	.57	.42 [c]	.03	.34 [e]	.09	.14 [e]	.49
ADOS								
Social affect	-.21 [f]	.29	.01 [f]	.96				
RRB	-.13 [f]	.51	-.25 [f]	.21				
Total	-.22 [f]	.28	-.10 [f]	.62				

Note. The upper section provides bivariate correlations between motion coherence thresholds in the limited and unlimited lifetime conditions and general developmental variables (age and IQ scores) and measures of autism symptomatology (Social Communication Questionnaire [SCQ; Rutter et al., 2003], Autism Diagnostic Observation Schedule [ADOS; Lord et al., 1999, 2012]). The lower section provides correlations between motion coherence thresholds and measures of autism symptomatology whilst controlling for age and full-scale IQ. VIQ = verbal IQ; PIQ = performance IQ; FSIQ = full-scale IQ; RRB = restricted and repetitive behaviour. N.b. ADOS scores were not obtained for typically developing children. A conservative significance level of $p < .01$ was adopted for all correlations.

[a] *df* = 29, [b] *df* = 28, [c] *df* = 26, [d] *df* = 27, [e] *df* = 24, [f] *df* = 25.

6.4 Discussion

In this study, children with autism and TD children aged 7 to 13 years were administered a motion coherence task under both limited and unlimited lifetime conditions, with slow-moving (1.5 deg/sec) stimuli. This manipulation allowed me to investigate whether the use of limited lifetime dots has a particularly disruptive effect on the motion coherence sensitivity of children with autism, in order to reconcile the discrepant results between Chapter 2 and Chapter 5. In line with adult studies (Braddick et al., 1998; Festa & Welch, 1997; Jackson et al., 2013), children had higher motion coherence thresholds (i.e., reduced sensitivity) when the dots moved with limited lifetime compared to when they moved with unlimited lifetime. Unexpectedly, however, the children with autism had comparable thresholds to the TD children, and were affected by limited lifetime to the same extent as TD children. In line with the findings from Chapter 2, greater levels of autistic symptomatology on the SCQ and ADOS were not related to motion coherence sensitivity in either condition.

The use of limited lifetime stimuli is normally justified as it precludes the tracking of single dots (e.g., Jackson et al., 2013; Milne et al., 2002). Therefore, it could be suggested that children are generally less sensitive to motion coherence stimuli in the limited lifetime condition as they are unable to rely on tracking strategies. However, it is unclear how tracking a single dot would lead to good performance at low levels of coherence. In this study, the mean threshold across groups was approximately 0.15 (15% coherence) in the unlimited lifetime condition. If an individual was tracking a single dot on a trial with 15% coherence, there would be an 85% chance of the individual tracking a randomly-moving noise dot, which would be unlikely to lead to the threshold of 75% accuracy in performance. Furthermore, it could be argued that tracking cannot be completely ruled out unless the lifetime is limited to only two frames (Lee & Lu, 2010). Another alternative is that the limited lifetime of dot stimuli introduces false correspondences between dots on successive frames, and this 'correspondence noise' elevates motion coherence thresholds (Barlow & Tripathy, 1997). In turn, correspondence noise may make the segregation of signal from noise more difficult (Watamaniuk et al., 2003).

Simmons et al. (2009) proposed that correspondence noise might present particular difficulties for children with autism. This suggestion provided a plausible explanation for why individuals with autism had elevated motion coherence thresholds in the slow speed condition of Chapter 2 (which had limited lifetime stimuli) and not in Chapter 5 (where dots moved with unlimited lifetime). However, the findings of the current study suggest that children with autism and TD children are equally affected by the dot lifetime manipulation, suggesting that children with autism are *not* more affected by correspondence noise than TD children.

These findings are in contrast with those measuring levels of autistic traits within the general population (Jackson et al., 2013). Jackson et al. (2013) presented adults with a motion coherence task in limited and unlimited lifetime conditions. The dots moved at a relatively slow speed (2.56 deg/sec) and the lifetime of dots in the limited lifetime condition was 80 ms – similar to the study reported here. Jackson et al. found that adults with high levels of autistic traits (measured by the AQ; Baron-Cohen et al., 2001) were more disrupted by limited lifetime stimuli than adults with low levels of autistic traits. In fact, high AQ-scorers showed *increased* sensitivity (i.e., lower thresholds) for unlimited lifetime stimuli compared to low AQ-scorers, and the extent of this group difference reduced in the limited lifetime condition. This result is intriguing given that increased sensitivity to motion coherence stimuli has never been reported in individuals with a clinical diagnosis of autism. The discrepancy between Jackson et al.'s results and the current results suggest that findings from individuals with high autistic traits may not generalise to individuals with a clinical diagnosis. Alternatively, the discrepancy could arise because different age groups were tested. However, it is unclear why children with high levels of autistic traits would be less affected by limited lifetime stimuli than adults with high levels of autistic traits.

It remains a challenge to explain why children with autism did not have elevated motion coherence thresholds in this study whereas they did in Chapter 2, particularly when the limited lifetime condition closely resembled that presented in Chapter 2. As noted in Section 6.2, four extra demonstration trials were presented in this study compared to the study reported in Chapter 2. This extra practice could have particularly benefited children with autism, allowing them to perform similarly to the TD children in the threshold estimation phase. Additionally, stimuli were presented on an LCD laptop screen rather than a CRT monitor in the current study. It is possible that children with autism may have been more sensitive to the discontinuous illumination or 'flicker' from the CRT monitor, potentially making them less sensitive to coherent motion. This account is plausible, given reports of atypical sensory sensitivities in individuals with autism (Section 1.2). Yet elevated motion coherence thresholds have been reported in individuals with autism using a range of screens (see Table 1.1), including both CRT monitors (e.g., Pellicano et al., 2005) and LCD monitors (e.g., Milne et al., 2002; Spencer et al., 2000). However, as with other task and stimulus parameters, the effect of different screen types can only be fully tested using a within-participants design.

Perhaps, then, the simplest explanation for the discrepancy between the results reported here and in Chapter 2 concerns the participants tested. The participants in Chapter 2 were similar in their ranges of age and ability (Table 2.1), and the same inclusion criteria were applied to both datasets. There were nine participants with autism and four TD participants who overlapped between the two studies, and it was confirmed that previous exposure to the task did not influence motion coherence thresholds (which is unsurprising given that the experiments were conducted 2 years apart). Furthermore, age and FSIQ were controlled throughout the analyses, which would have minimised the effects of differing age and ability. However, the findings in Chapter 2 clearly showed that not all children with autism have elevated motion coherence thresholds. It is possible therefore that there were fewer children with autism in the current study who have reduced coherent motion sensitivity compared to in the study reported in Chapter 2. While we could not detect a clear subgroup of children with autism with elevated thresholds in Chapter 2, it is possible that such a subgroup may be difficult to detect with the sample sizes used. Furthermore, it remains a possibility that those children with autism who *do* show elevated thresholds may be more susceptible to the correspondence noise associated with limited lifetime stimuli, as proposed by Simmons et al. (2009).

In sum, this study shows that children with autism are equally affected by a limited lifetime manipulation as TD children, suggesting that children with autism are *not* more affected by correspondence noise than TD children (c.f., Simmons et al., 2009). Thus, correspondence noise does not offer an explanation for the discrepancy between the elevated thresholds of children with autism compared to TD children in Chapter 2 and the lack of group differences in thresholds in Chapter 5. Importantly, elevated thresholds were not found in the current study, despite using the same task as in Chapter 2. Consequently, the simplest explanation for elevated thresholds in Chapter 2, but not in either the current study or Chapter 5, appears to be between-participant variability. Reduced sensitivity to coherent motion does not therefore appear to be a general difficulty common to all children with autism. The implications of this conclusion will be discussed fully in the final chapter.

7 General discussion

7.1 Introduction

In this thesis, I aimed to characterise better atypical sensory processing in autism, focusing on one critical aspect of visual development: motion processing (Section 1.4). The studies within this thesis used child-friendly psychophysical methods in order to measure sensitivities to motion information in children with autism and typically developing (TD) children (Chapters 2, 4, 5 and 6). These findings were supplemented with an exploratory study into children's everyday speed perception abilities, as assessed by a new parent-report questionnaire (Chapter 3). First, I shall summarise the main findings from this thesis regarding speed discrimination, motion coherence sensitivity, and direction integration in children with autism and TD children, and propose some general principles relating to motion processing in childhood (Section 7.2). I will then explain how the findings from this thesis have furthered the field of motion processing in autism (Section 7.3) and relate the results to existing theoretical accounts of atypical motion processing in autism (Section 7.4). Next, I will consider the main implications of the findings reported in this thesis (Section 7.5) before considering the limitations of the research (Section 7.6). Finally, I will suggest some future directions that will help further to elucidate both the *nature* of atypical motion processing in autism and the *mechanisms* underlying such atypicalities, as well as to bridge the gap between psychophysical task performance and everyday functioning (Section 7.7).

7.2 Summary of main findings

7.2.1 Speed processing

Chen et al. (2012) previously investigated speed discrimination in autistic adolescents aged 13 to 18 years, and found no differences in sensitivity for a short interstimulus interval (ISI), but *enhanced* sensitivity for a long ISI. In contrast, Chapter 2 investigated speed discrimination abilities in *children* with autism aged 7 to 14 years, for whom speed discrimination abilities are still developing (C. Manning et al., 2012). This was the first study to compare sensitivities for slow (1.5 deg/sec) and fast (6 deg/sec) reference speeds in individuals with autism, motivated by evidence of distinct developmental trajectories for different speeds (C. Manning et al., 2012). Unexpectedly, children with autism were just as sensitive to speed differences as TD children, for both slow and fast reference speeds. As this is only the second study to investigate speed discrimination abilities in individuals with autism, our understanding of speed perception in individuals with autism is still in its infancy. In light of Chen et al.'s intriguing finding that adolescents with autism show *enhanced* speed discrimination with a longer ISI, it is important to investigate the importance of different stimulus parameters on speed perception in children with autism. Just as stimulus parameters appear to be important for determining coherent motion sensitivity in individuals with autism (e.g., C. E. Robertson et al., 2012; Ronconi et al., 2012; Chapter 2), they are likely to contribute to speed sensitivity.

Chapter 3 analysed parents' responses to a questionnaire asking about their child's speed perception in everyday life. Parents of children with autism reported more speed-related atypicalities than parents of TD children, which concurs with autobiographical reports from autistic adults (Grandin, 1995; D. Williams, 1999).

Responses to the questionnaire revealed three factors: Difficulties Processing Speed-related Information, Distress Towards Moving Objects and Enjoyment Watching Repetitive Movements. The parents of children with autism reported more Difficulties Processing Speed-related Information than parents of TD children. However, there were no group differences in Enjoyment of Watching Repetitive Movements or Distress Towards Moving Objects, which may be because these behaviours are reported less frequently overall. The scale was highly reliable, suggesting that it may be a useful tool for future research into everyday speed perception in children with autism. However, the factor structure will require validation within a larger sample of both children with autism and TD children.

There was no relationship between speed discrimination thresholds and factor scores, suggesting that the everyday speed difficulties faced by children with autism are not captured by the psychophysical task used. Indeed, there may not be a simple one-to-one mapping between behaviour and underlying perception during development (Karmiloff-Smith, 2009). An unresolved question, therefore, is what factors contribute to parent-reported speed processing atypicalities. It is possible that everyday speed processing tasks rely on interactions between perceptual and motor systems, and are of greater complexity than the psychophysical task, which merely required the comparison of two sequentially presented speeds. Additionally, it is possible that everyday speed processing abilities are related to psychophysical task performance when assessed via self-report.

7.2.2 Motion coherence perception

Relative to speed discrimination, motion coherence sensitivity has been extensively investigated in individuals with autism. However, the evidence is mixed, with some studies, but not all, reporting elevated thresholds in individuals with autism (see Section 1.5.2 and Table 1.1). In this thesis, motion coherence tasks were given to children with autism and TD children in Chapters 2, 5 and 6. Two out of these three studies (Chapters 5 and 6) found no evidence of motion coherence difficulties in children with autism. Meanwhile, Chapter 2 found elevated motion coherence thresholds for children with autism, but only for a slow (1.5 deg/sec) and not a fast (6 deg/sec) stimulus speed. Stimulus parameters have previously been shown to be important in determining whether individuals with autism display elevated motion coherence thresholds (C. E. Robertson et al., 2012; Ronconi et al., 2012), and Chapter 2 appeared to suggest that stimulus speed was another important parameter. However, Chapter 6, which used the same stimuli and methods as Chapter 2, did not replicate the finding of elevated motion coherence thresholds at a slow stimulus speed. Furthermore, Chapter 6 showed that children with autism were affected by limited lifetime dots to the same extent as TD children.

It remains a challenge to explain the discrepant motion coherence results reported within this thesis. In all studies, there was a considerable overlap between the motion coherence thresholds of children with autism and those of TD children, suggesting that the majority of children with autism perform within the typical range. However, some children with autism may be less sensitive to coherent motion information, in particular for slow speeds (Chapter 2). Whether group differences emerge or not may depend on the proportion of these children within the sample. An interesting avenue for future research may determine why some children with autism have reduced sensitivity to coherent motion information. It is possible that sensitivity to motion information is related to sensory subtypes in children with autism, although currently there is no consensus at what these subtypes are (see Ausderau et al., 2014;

Lane, Molloy, & Bishop, 2014). Overall, this thesis suggests that there are no general, pervasive difficulties in motion coherence sensitivity in children with autism.

7.2.3 Direction integration performance

In Chapters 4 and 5, I assessed direction integration in children with autism and TD children using an equivalent noise paradigm. In this task, participants were asked to compute the average stimulus direction under two conditions: one with no noise (no directional variability) and one with high levels of noise. Unlike the motion coherence task, performance in the equivalent noise task does not rely on the ability to segregate motion information, as the optimal strategy is to average all information. Therefore, the equivalent noise task yields a purer measure of integration ability. The equivalent noise motion integration task has so far been used primarily with adults (but see Bogfjellmo et al., 2014, for an exception). It was therefore important to validate the use of the task with children and to establish what limits motion coherence sensitivity in TD children, before investigating how this might differ in children with autism. I found that levels of internal noise reduced through childhood, while the number of samples that could be averaged increased. Age-related improvements in motion coherence sensitivity, however, were driven by averaging and not internal noise.

In Chapter 5, children with autism performed similarly to TD children when discriminating directions in the absence of directional noise, but could compute the average direction over a greater range of directional variability than TD children. Equivalent noise modelling suggested that children with autism had typical levels of internal noise, and could effectively sample over more dots than TD children to make their decisions. Analysing the data from Chapters 4 and 5 together revealed that children with autism were performing at adult-like levels in their ability to average motion information. Replication of these unexpected findings is crucial given the pattern of mixed findings in the motion coherence literature. However, I speculate that the increased integration reported here may be a more robust effect than elevated motion coherence thresholds. Accordingly, the effect sizes reported for estimates of maximum tolerable noise ($\eta_p^2 = .21$) and sampling ($\eta_p^2 = .19$) in Chapter 5 were greater than that reported for elevated motion coherence thresholds for slow speeds in Chapter 2 ($\eta_p^2 = .12$).

7.2.4 Motion processing in childhood: General principles

Although a range of different motion processing tasks have been used in this thesis, a set of general principles have emerged relating to the development of motion processing. I outline these principles in the following section.

7.2.4.1 Children are variable in their motion processing abilities.

One of the most pertinent features of the threshold data from both TD children and children with autism is the extent of variability between participants. Arguably, inter-individual variability is to be expected in children with autism, given the wide heterogeneity in symptom profiles encompassed by a diagnosis of autism (Section 1.1.2). However, the TD children also show a similar extent of variability. For example, in Chapter 4, there are some 5-year-olds who are more sensitive to motion information than certain adult participants (Figure 4.6 and Figure 4.7). Due to the large variability in performance in both children with autism and TD children, there is often a considerable degree of overlap between children with autism and TD children, even when the groups differ in their means. Future research will be needed to understand what factors contribute to this large inter-participant variability. While general developmental variables such as age and IQ are potentially good candidates, these are not consistently related to task performance in the studies reported here (Sections 2.3.5.1, 5.3.8.1, and 6.3.2.1). Given the extent of variability between participants, it is important to use within-participants designs wherever possible when studying motion processing in development, and to use large sample sizes when attempting to detect between-participants differences.

7.2.4.2 Processing slow motion is difficult.

A strong finding emerging from Chapters 2, 4 and 5 is that the processing of slow (1.5 deg/sec) motion is more difficult than the processing of fast (6 deg/sec) motion, for both TD children and children with autism. In fact, a within-participants effect of speed was reported in all tasks: speed discrimination (Chapter 2), motion coherence (Chapters 2, 4 and 5), and both conditions of the equivalent noise direction integration task (Chapters 4 and 5). These findings are consistent with previous investigations into the development of speed discrimination (Ahmed et al., 2005; Aslin & Shea, 1990; C. Manning et al., 2012; Volkmann & Dobson, 1976) and coherent motion perception (Hadad et al., 2011; Hayward et al., 2011; Narasimhan & Giaschi, 2012).

Furthermore, I reported that processing slow motion may be particularly difficult for some children with autism (Chapter 2). This finding is paralleled by studies showing reduced motion sensitivity specifically for slow stimuli in other conditions, such as amblyopia (Hayward et al., 2011) and dyslexia (V. T. Edwards et al., 2004). Elevated motion thresholds for slow stimuli may arise in some individuals with developmental conditions because the ability to process slow motion follows a more extended trajectory than that to fast speeds (Hayward et al., 2011; C. Manning et al., 2012), making it more vulnerable to atypical development.

It has previously been suggested that differential sensitivities for slow and fast stimuli reflect different channels tuned for slow and fast motion (Section 1.4.1). The results from Chapter 4 help to further elucidate the mechanisms underlying reduced sensitivity to slow motion, as higher levels of internal noise and reduced levels of sampling were associated with processing slow motion (1.5 deg/sec) compared to fast motion (6 deg/sec) in typical development. Indeed, reduced sampling for slow speeds could be a psychophysical correlate of fewer neurons tuned to slow speeds, which has previously been demonstrated in the adult monkey brain (J. Liu & Newsome, 2003). It has also been suggested that the parvocellular/ventral stream is involved in processing slow speeds (Gegenfurtner & Hawken, 1996; Hammett et al., 2005; Lorteije et al., 2008; Perrone, 2005; see also review by Burr & Thompson, 2011), making it possible that reduced sensitivity to slow speeds in childhood reflects immature parvocellular/ventral stream processing.

Reduced sensitivity to slow speeds (or heightened sensitivity to fast speeds) might also be understood within an evolutionary framework. Objects moving slowly across the retina may either be actually moving at a slow speed, or they may be a long distance away, both giving the observer a long time to prepare a response to the object. In contrast, objects moving fast across the retina may be more immediate, where it is important to reliably and accurately judge the speed and direction of an object in order to organise a response to it.

Most research comparing the development of sensitivities to slow and fast speeds has compared slow to moderately fast speeds. For example, in this thesis and in studies by Ahmed et al. (2005) and C. Manning et al. (2012), sensitivities were compared for stimulus speeds of 1.5 deg/sec and 6 deg/sec. Other studies have similarly compared thresholds for stimulus speeds between 0.1 deg/sec and 18 deg/sec (Ellemberg et al., 2004; Hadad et al., 2011; Hayward et al., 2011; Narasimhan & Giaschi, 2012). However, no research has investigated children's sensitivities to very fast speeds. In adults, speed sensitivity follows a U-shaped curve, with an optimal range between 4 and 64 deg/sec (de Bruyn & Orban, 1988), and poorer discrimination at speeds below and above this. It is not yet clear what the optimal range for children is, and whether children also show a U-shaped sensitivity profile with higher thresholds for very high speeds. It could be that children show pronounced immaturities for processing both slow and fast speeds that fall outside the optimal range.

It has been suggested that differential sensitivity to slow and fast stimuli reflects sensitivities to specific combinations of spatial and temporal offsets rather than sensitivities to speed information per se, in both children (Ellemberg et al., 2010; Meier & Giaschi, 2014) and adults (Arena, Hutchinson, & Shimozaki, 2012; Ellemberg et al., 2010). However, the contributions of spatial and temporal offsets can only be disentangled in apparent motion displays in the laboratory. It is unclear how such dependence on spatial and temporal offsets might relate to processing motion information in everyday life.

7.2.4.3 Limited lifetime stimuli disrupt coherent motion processing.

Studies of motion processing often use limited lifetime random dot stimuli (Britten et al., 1992; Newsome & Paré, 1988; see Table 1.1) to preclude the use of tracking strategies. However, as highlighted in Chapter 6, there are many reasons that limited lifetime may elevate motion coherence thresholds, besides the elimination of tracking strategies. For example, limited lifetime dots increase correspondence noise, which has been proposed to have a particularly disruptive effect on motion perception in children with autism (Simmons et al., 2009). Chapter 6 showed that both children with autism and TD children had elevated thresholds in a limited lifetime condition compared to an unlimited lifetime condition. Unexpectedly, however, children with autism were affected by this manipulation to a similar extent as TD children. Therefore, problems dealing with correspondence noise do not appear to be specific to children with autism. Moreover, pilot studies revealed that some adult participants could not perceive the direction of 100% coherently moving stimuli in Chapter 4, again suggesting that limited lifetime disrupts motion processing. Future research may consider whether the use of limited lifetime stimuli disrupts the performance of children to a greater extent than adults.

7.3 Contributions to the field

As reviewed in Section 1.5, motion processing has been fairly extensively investigated in autism. However, the majority of studies have used the motion coherence paradigm, which has produced a plethora of mixed findings (Table 1.1). The reliance on the motion coherence paradigm has therefore left the field of motion processing in autism stagnant. The studies reported in this thesis demonstrate that elevated motion coherence thresholds are not found consistently in children with autism (Chapters 2, 5 and 6) and highlight that there are multiple reasons why an individual can perform poorly on a motion coherence task (Chapters 4 and 5). It is therefore not clear how to interpret reports of elevated motion coherence thresholds in studies that *do* report group differences. Arguably, the most interesting and unexpected findings concerning motion processing in autism have arisen from studies that go beyond the traditional motion coherence paradigm (e.g., Chen et al., 2012; Foss-Feig et al., 2013). However, replication efforts are required to ensure that these findings are not spurious.

Similarly, the studies reported in Chapters 2 and 5 test motion processing abilities that have so far received little attention in autism. Chapter 2 shows that the ability to discriminate speed differences is typical in children with autism, and Chapter 5 shows that the ability to average motion information within an equivalent noise task is *enhanced* in children with autism. Divergence from the motion coherence paradigm has therefore led to new insights into motion processing in autism, which will serve to progress the field. Importantly, the research within this thesis highlights that motion coherence performance cannot be assumed to reflect integration abilities. Indeed, in order to measure integration abilities, a purer task must be used, such as the equivalent noise paradigm, which eliminates segregation demands.

The distinction between integration and segregation demands may also provide a useful framework for understanding previous findings. I provide three examples here. First, difficulties segregating motion information could explain previous reports of reduced multiple object tracking (MOT) ability in individuals with autism (Koldewyn, et al., 2013; O'Hearn et al., 2013). Successful performance on these tasks requires distinct representations of each individual object's motion to be maintained, which would be sacrificed if individuals integrated across object motions. Second, the rare reports of enhanced sensitivity to motion information in individuals with autism have emerged from tasks that do not require segregation of signal from noise (Chen et al., 2012; Foss-Feig et al., 2013). Third, it has been suggested that biological motion sensitivity may be reduced in autism due to an inability to exclude noise (McKay et al., 2006; Simmons et al., 2009). While it is difficult to fully separate the contributions of integration and segregation to motion processing, this may be a worthwhile effort in order to understand atypical motion processing in autism.

7.4 Theoretical perspectives

I now revisit the existing accounts of atypical motion processing outlined in Section 1.6, and relate them to the findings reported in this thesis. Finally, I consider how the results relate to a theory of autistic perception that has so far focused primarily on static perception: the increased perceptual capacity account.

7.4.1 Dorsal/magnocellular accounts

It has been suggested that motion processing may be disproportionately affected in a range of developmental conditions, due to an increased vulnerability of the dorsal (Braddick et al., 2003) or magnocellular (Greenaway et al., 2013) pathway compared to the ventral and parvocellular pathways. Such accounts have the potential to explain reduced sensitivity to motion information in a range of developmental conditions. However, the pattern of motion processing abilities in children with autism that are reported in this thesis appears too complex for these accounts. If the magnocellular and/or dorsal stream were vulnerable to developmental insult, pervasive difficulties would be expected in many aspects of motion processing in children with autism. Yet, only one instance of reduced sensitivity to motion information was reported in this thesis: elevated motion coherence thresholds for slow (1.5 deg/sec) stimuli (Chapter 2), and this finding was not replicated in Chapter 6.

The fact that some children with autism appear to have reduced sensitivity specifically for slow speeds is particularly problematic for dorsal/magnocellular accounts given evidence that slow motion may be processed by the parvocellular/ventral stream (Gegenfurtner & Hawken, 1996; Hammett et al., 2005; Lorteije et al., 2008; Perrone, 2005). Even more problematic for accounts of impaired dorsal/magnocellular function are findings emerging from Chapter 5, which demonstrate an *enhanced* aspect of motion processing: direction integration. It therefore appears that children with autism do not experience pervasive difficulties in motion processing, and on the contrary, show evidence of increased sensitivity to motion information in some tasks (Chapter 5; see also Chen et al., 2012; Foss-Feig et al., 2013).

7.4.2 Local versus global and complexity accounts

A distinction between local and global processing has previously provided a framework for understanding reduced sensitivity to motion information in some tasks (Milne et al., 2002; Pellicano et al., 2005) and unimpaired – and sometimes even enhanced – sensitivity in other motion-processing tasks (Bertone, Mottron, Jelenic, & Faubert, 2003, 2005; Chen et al., 2012; Foss-Feig et al., 2013; Pellicano et al., 2005). One major theory distinguishing between local and global processing is Weak Central Coherence (WCC; Frith & Happé, 1994; Happé & Booth, 2008). According to this theory, individuals with autism have difficulties with motion processing tasks that require integration and involve higher-order areas of the visual processing hierarchy (Section 1.4.1). However, previous studies have focused on the motion coherence paradigm, which does not unambiguously measure integration performance. As highlighted in Chapter 4, motion coherence sensitivity could also be limited by increased levels of internal noise and/or by difficulties segregating signal from noise.

In Chapter 5, I reported that children with autism showed *enhanced* averaging of direction information compared to TD children. This finding therefore poses a serious challenge to accounts that propose that individuals with autism have difficulties integrating motion information. The Enhanced Perceptual Functioning theory (EPF; Mottron et al., 2006) does not posit a weakness in global integration, but instead proposes enhanced local processing. Nevertheless, the results from Chapter 5 do not support this account either, as children with autism appeared to show typical local processing of direction information, and *enhanced* global processing. However, an aspect of Reduced Generalisation Theory (RGT; Plaisted, 2001) resonates with my proposal that children with autism have difficulties segregating signal from noise. According to Plaisted (2001), individuals with autism have enhanced processing of individual stimulus features, which may mean that randomly moving noise dots in the motion coherence task are perceived as important, salient features and are therefore not filtered out by children with autism to the same extent as by TD children.

7.4.3 Temporo-spatial processing disorders

The temporo-spatial processing disorders hypothesis posits that individuals with autism have difficulties with motion processing because they are poorer at integrating across space and time than TD individuals (Gepner & Féron, 2009; Gepner et al., 2005, 2010). In this thesis, I have reported multiple instances where children with autism perform comparably to TD children in tasks that require extensive integration across space and time (e.g., speed discrimination, Chapter 2; motion coherence, Chapters 5 and 6; fine direction discrimination, Chapter 5). A further prediction arising from the temporo-spatial processing disorders hypothesis is that individuals with autism should be particularly impaired at processing fast motion. Chapter 2 directly opposed this hypothesis, with children with autism having elevated motion coherence thresholds compared to TD children only at a slow (1.5 deg/sec) and not a fast (6 deg/sec) reference speed. Moreover, children with autism performed significantly better than TD children in a task directly testing integration abilities (Chapter 5). Therefore, difficulties integrating across space and time do not provide a good account of the motion processing abilities of children with autism reported in this thesis.

A related account was proposed by C. E. Robertson et al. (2012), who suggested that motion integration is atypical in individuals with autism, specifically in the temporal domain. This suggestion appeared to explain why these authors found elevated motion coherence thresholds only with a short stimulus duration (200 ms) and not with longer stimulus durations (400, 1500 ms). Conversely, in this thesis, elevated thresholds were found when a long stimulus duration was used (1000 ms) in Chapter 2, but not when a shorter stimulus duration (400 ms) was employed in Chapter 5. However, the motion coherence tasks used in Chapters 2 and 5 differed in many stimulus parameters other than duration (Section 5.4) and different participants were tested, making it impossible to make a direct comparison.

Yet the findings from Chapter 6 also speak against C. E. Robertson et al.'s (2012) account. If children with autism integrate motion information atypically in the temporal domain, it would be expected that the motion coherence performance of children with autism would be more affected by limited lifetime than TD children (Festa & Welch, 1997). Yet, children with autism were similarly affected by the dot lifetime manipulation in Chapter 6 as TD children, suggesting that temporal integration is typical in children with autism.

7.4.4 Extreme male brain theory

It was outside the scope of this thesis to directly test the extreme male brain theory as an explanation for atypical motion processing in autism, as no measures of foetal testosterone (e.g., 2D:4D ratio; Falter et al., 2008; Milne et al., 2006) were collected. However, there is currently no clear evidence to suggest that foetal testosterone is related to visuospatial processing ability (Auyeung et al., 2012; Falter et al., 2008), and it is unclear how this hormone would lead to typical levels of performance in some tasks (e.g., speed discrimination), but elevated thresholds and lower thresholds in other tasks (e.g., direction integration).

7.4.5 Neural noise accounts

Accounts of both increased internal noise (Simmons et al., 2009) and reduced internal noise in autism (G. Davis & Plaisted-Grant; in press) have been previously proposed. Chapter 5 aimed to investigate whether atypical levels of internal noise contributed to elevated motion coherence thresholds in children with autism using an equivalent noise paradigm. I found no evidence for atypical levels of (local) internal noise in the direction integration task. However, the interpretation of the results from the equivalent noise modelling is complicated as children with autism did not benefit from increased sampling when there was no directional noise in the stimulus (Section 5.4). Future research is therefore needed to confirm the finding of typical levels of internal noise in children with autism for a direction integration task. However, the finding that children with autism can integrate over a greater range of directional variability than TD children (Chapter 5) speaks against G. Davis and Plaisted-Grant's (in press) account which posits poor integration as a result of enhanced discriminability of individual stimulus elements. Instead, the findings reported in Chapter 5 are potentially consistent with reduced *global* noise in autism. The possibility that children with autism have typical levels of local noise but atypical global noise emphasises the importance of specifying the level at which atypical levels of noise are expected to have an effect in noise accounts of autistic perception.

7.4.6 Reduced top-down influences

The studies reported in this thesis were not designed to test the hypothesis that children with autism are less influenced by top-down influences (Greenaway & Plaisted, 2005; Mitchell et al., 2010; Pellicano & Burr, 2012; Ropar & Mitchell, 2002). Nevertheless, a pattern of increased integration abilities and reduced segregation abilities could be understood within a Bayesian framework (Pellicano & Burr, 2012). Children with autism may not use accumulated knowledge about what is relevant and irrelevant in the world in order to filter certain information out, as a consequence of attenuated priors (‘hypopriors’). Interestingly, it is possible that reduced adaptation to motion information (as a result of attenuated priors) may lead to subjective experiences of the world moving too fast (Chapter 3; Grandin, 1995; D. Williams, 1999). I suggest ways of testing this account in Section 7.7.

7.4.7 Increased perceptual capacity

An account that fits well with the finding of enhanced direction integration in children with autism is the increased perceptual capacity account (Remington et al., 2009, 2012). This account is rooted within the field of attention research and visual search paradigms, and has therefore not been applied previously to motion processing in autism. According to the increased perceptual capacity account, individuals have a finite capacity for processing perceptual information, which is larger in individuals with autism than TD individuals. Increased capacity can lead to enhanced performance in visual search tasks by individuals with autism, but can also lead to increased distractibility due to increased processing of distracters (Remington et al., 2009, 2012). An increased capacity for processing motion information could lead to increased integration of direction information. Interestingly, the randomly-moving noise dots in the motion coherence task can be thought of as distracters. Children with autism may process these distracters more extensively than TD children due to their increased perceptual capacity, which might explain why children with autism do not benefit from an increased capacity in the motion coherence task. In this manner, the increased perceptual capacity account concords with the pattern of increased integration and reduced segregation abilities in children with autism proposed in this thesis.

However, the increased perceptual capacity account provides only a re-description of the findings, and provides little additional explanatory power. It is therefore important to understand what mechanisms might underlie increased perceptual capacity. One candidate is larger extrastriate population receptive fields in individuals with autism (Schwarzkopf et al., 2014), although this possibility needs to be confirmed in children with autism. In the study reported in Chapter 5, children with autism are not only processing *more* information, they are also able to effectively integrate this information to compute an average direction. Future research will be required to determine whether the ability to compute summary statistics is related to increased perceptual capacity, as measured by attention paradigms.

7.4.8 Summary of theoretical approaches

Accounts positing general difficulties in motion processing (e.g., dorsal stream vulnerability hypothesis, Braddick et al., 2003; temporo-spatial processing disorders hypothesis, Gepner & Féron, 2009) are unable to explain the reports of unimpaired and enhanced sensitivity to motion information within this thesis. Furthermore, the finding of enhanced integration of direction information opposes previous conceptualisations of local and global processing in children with autism (e.g., WCC, Frith & Happé, 1994; EPF, Mottron et al., 2006). A more promising approach for understanding the pattern of motion processing abilities in children with autism lies in theories that can account for both increased integration and reduced segregation abilities, such as the increased perceptual capacity account (Remington et al., 2009, 2012) and the 'hypopriors' account (Pellicano & Burr, 2012). An important strength of the dorsal stream vulnerability hypothesis (Braddick et al., 2003), however, is that it is a developmental account, based on the typical development of motion processing. Such a developmental aspect should be incorporated into future accounts of motion processing in autism – for example, to explain how increased perceptual capacity (Remington et al., 2009, 2012) or 'hypopriors' (Pellicano & Burr, 2012) might emerge in children with autism.

7.5 Implications of research

7.5.1 Specificity of atypical motion processing in autism

Elevated motion coherence thresholds have been reported in a range of developmental conditions, such as Williams Syndrome (J. Atkinson et al., 1997, 2006; c.f., Palomares & Shannon, 2013), dyslexia (Demb et al., 1998; Hansen et al., 2001), Fragile X syndrome (Kogan et al., 2004) and schizophrenia (Chen, Nakayama, Levy, Matthysse, & Holzman, 2003). It is therefore an interesting question whether atypical motion processing is specific to different developmental conditions, or is a general consequence of atypical development.

Elevated motion coherence thresholds have not only been reported specifically for slow stimulus speeds in children with autism (Chapter 2), but also in children with dyslexia (V. T. Edwards et al., 2004) and amblyopia (Hayward et al., 2011). However, it is not clear what leads to elevated motion coherence thresholds in these different conditions. Moving away from the motion coherence paradigm therefore has the potential to address whether atypical motion processing is condition-specific.

Chapter 2 showed that children with autism have comparable sensitivities to speed information as TD children. In contrast, *elevated* speed discrimination thresholds have been reported in individuals with developmental dyslexia (Wilmer, Richardson, Chen, & Stein, 2004) and schizophrenia (Clementz, McDowell, & Dobkins, 2007; although this may reflect abnormal eye movements: Hong et al., 2009). The equivalent noise paradigm will also allow new insights into the specificity of atypical motion processing in autism, by revealing the factors that limit motion coherence thresholds in different conditions. Reduced segregation has previously been proposed as a mechanism for elevated motion coherence thresholds in dyslexia (Sperling et al., 2005, 2006), although the equivalent noise paradigm has not yet been used with this population. As far as I am aware, there are no reports of *increased* integration of direction information in other developmental conditions. Therefore, the results from this thesis suggest that the pattern of motion processing atypicalities found in autism is distinct from those found in other conditions.

7.5.2 The effect of atypical motion processing on the everyday lives of children with autism

If children with autism show a distinct pattern of motion processing atypicalities compared to children with other developmental conditions, the next logical step is to consider how these atypicalities are related to the specific set of symptoms associated with autism. Motion processing thresholds were not consistently related to measures of autistic symptomatology (Social Communication Questionnaire [SCQ; Rutter et al., 2003]; Autism Diagnostic Observation Schedule [ADOS-G; ADOS-2; Lord et al., 1999, 2012]) within the studies reported in this thesis. However, it is likely that atypical motion processing relates more strongly to non-social symptoms than social symptoms (Mandy, Charman, & Skuse, 2012), and the SCQ and ADOS may not be sensitive enough to detect low-frequency non-social symptoms. It is possible that increased integration of motion information, combined with reduced filtering of irrelevant information, may lead to feelings of sensory overload reported in children with autism (Kirby et al., 2014; Pellicano, 2013). Chapter 3 suggested that atypical motion processing might be related to motor skills in children with autism, as measured by parent-report questionnaires. Future research will be needed to clarify the role that atypical motion processing plays in everyday abilities such as catching a ball, or crossing a road. In particular, objective measures of motor skills (such as the Movement Assessment Battery for Children; Henderson, Sugden, & Barnett, 2007) may allow the relationship between atypical motion perception and movement production to be studied more directly (see also Milne et al., 2006; Price et al., 2012).

7.5.3 Coherent motion perception is just one form of global motion perception

To date, the term ‘coherent motion perception’ has been used synonymously to mean ‘global motion perception’. However, this thesis highlights that coherent motion perception is only one form of global motion perception, and therefore elevated thresholds in a motion coherence task do not imply reduced sensitivity to all classes of global motion perception. This distinction is demonstrated in Chapter 5, whereby children with autism showed enhanced direction integration compared to TD children, yet comparable sensitivity in a motion coherence task. Global motion perception involves both integration and segregation of local motion information, and it is therefore important to specify precisely the nature of global motion perception being assessed in any given task (see also de-Wit & Wagemans, in press; Wagemans et al., 2014).

7.6 Limitations of research

Throughout this thesis, the motion processing performance of children with autism was compared to that of age- and ability-matched TD children. All children were cognitively able (with IQ scores above 70), both to ensure that children understood task instructions and to facilitate matching between groups. Therefore, it is unclear whether the findings reported in this thesis would generalise to cognitively less able children with autism. Furthermore, the majority of children with autism who participated in these studies were male, as it was difficult to recruit cognitively able girls with autism. Recent research has suggested that girls and boys with autism may have different phenotypes (Head, McGillivray, & Stokes, 2014; Mandy, Chilvers, et al., 2012), suggesting that it will be important to compare groups of girls and boys on the tasks presented within this thesis. Thus at present, it cannot be stated that the finding of enhanced integration of direction information (Chapter 5) generalises to children across the whole autism spectrum.

In Chapter 4, age-related changes in the motion processing abilities of TD children were measured using a cross-sectional design. However, there is a large amount of between-participants variability (Section 7.2.4.1), which may mask the full extent of age-related changes. A much stronger design for investigating developmental changes is a longitudinal design, which follows the same children at different time points. However, such a longitudinal design is both resource- and time-intensive, and was therefore not possible within this thesis. On a related note, I was not able to properly investigate developmental changes in children with autism. Groups of approximately 30 to 40 children with autism were recruited for each study reported in Chapters 2, 5 and 6. These sample sizes are larger than many comparable studies that have examined motion processing in individuals with autism (Table 1.1). However, even larger samples would be required to fully investigate developmental changes in children with autism, when a longitudinal design is not possible.

Well-controlled psychophysical experiments are essential for probing the sensory functioning of individuals with autism. However, it is currently unclear how performance in psychophysical tasks translates to the sensory atypicalities experienced by children with autism in everyday life. The results of the parent-report questionnaire (Chapter 3) suggested that children with autism process speed-related information atypically in everyday life, yet these did not relate to the psychophysical measures reported in Chapter 2. In future studies, it may be beneficial to collect more measures of sensory functioning from children and their parents, for example by administering sensory questionnaires such as the Sensory Profile (Dunn, 1999) or interviewing children (R. A. O. Davis et al., 2006; Kirby et al., 2014).

Throughout this thesis, thresholds were measured as carefully and accurately as possible. However, it is worth noting that psychophysical studies with children, such as those reported in this thesis, sacrifice some of the methodological rigour that is possible in psychophysical studies conducted on adults. For example, children were seen in a range of different settings (e.g., at school, at home, or at the Institute of Education) and light and noise levels in the testing locations could not be tightly controlled. While different settings and light levels might potentially contribute to between-participants variability (Section 7.2.4.1), these factors are likely to be negligible when comparing performance at the group level and when investigating within-participants effects.

Ideally, more extensive visual screening could have been conducted with the children. In reality, far-distance acuity (as measured by letter acuity charts) may not be important for performance on tasks that are presented on a computer ~50 cm away from the participant. A more extensive battery could have included a test of near-distance acuity, stereoacuity, and a measure of the visual field. However, it was deemed important to reduce the amount of time that children and their families gave up to take part in the research. Furthermore, it is not clear how the complex pattern of motion processing abilities in children with autism reported in this thesis can be explained on the basis of optical factors.

In Chapters 4 and 5, an eyetracker was used to measure fixation behaviour during the psychophysical tasks. This technology provided useful information about whether a child was maintaining central fixation. Ideally, therefore, fixation behaviour would have been collected in all studies. However, an eyetracker was not available for use in the studies reported in Chapters 2 and 6. Importantly, however, fixation stability was not related to any psychophysical measure in children with autism in Chapter 5, suggesting that this cannot account for the psychophysical results reported.

Some parents of children with autism reported that their children with autism had co-occurring disorders, such as attention deficit/hyperactivity disorder (AD/HD). Due to difficulties teasing these conditions apart (Section 1.1.3) and inconsistencies in diagnoses, these participants were not excluded in the analyses reported in this thesis. Indeed, it is probable that some children with autism have additional difficulties (e.g., attention difficulties) even when they have not been given an official diagnosis. Therefore, it may have been useful to collect trait measures for other developmental conditions (e.g., the Conners' Parent Rating Scale to measure traits of AD/HD; Conners, Sitarenios, Parker, & Epstein, 1998) to assess how such traits are related to motion processing performance. Trait measures were not collected in the studies reported in this thesis in order to reduce the amount of questionnaires that parents were required to complete, although this could be a worthwhile addition to future research.

7.7 Future directions

I now suggest three avenues for future research that broadly serve to 1) improve our understanding of the *nature* of motion processing in autism, 2) uncover the *mechanisms* behind atypical motion processing in autism, and 3) bridge the gap between performance in psychophysical tasks and everyday functioning.

7.7.1 Understanding the nature of motion processing in autism

As previously highlighted in this thesis (Sections 1.5.4 and 7.2.1), the processing of speed information by individuals with autism has received little attention. Indeed, this thesis presents only the second study to investigate speed discrimination in individuals with autism (Chapter 2). The children with autism in Chapter 2 showed comparable sensitivities to speed information as TD children, yet elevated motion coherence thresholds for a slow speed condition. While this could suggest that speed information and direction information are processed differently (Section 1.4.1), it could be that the tasks were not comparable. The results from Chapter 5 suggest that children with autism have superior integration of direction information, but may have difficulties segregating signal from noise. It would be interesting to see whether this is also the case for processing speed information. In particular, it would be useful to investigate whether children with autism show superior averaging of speed information in an equivalent noise speed integration task (e.g., Chen, Norton, & McBain, 2014) and whether they perform similarly to TD children in an adapted form of a motion coherence task, whereby children are required to compute the coherent speed amongst noise dots moving at random speeds. Future research should also investigate the importance of stimulus parameters in determining sensitivity to speed information in children with autism, as stimulus parameters have been shown to be important in motion coherence sensitivity (C. E. Robertson et al., 2012; Ronconi et al., 2012).

It is still not clear whether atypical motion processing is specific to the motion domain, or generalisable to other (i.e., static) tasks. Some research suggests that motion processing is more affected in autism than form processing (Spencer et al., 2000) whereas other reports suggest that atypical motion processing goes hand-in-hand with atypical form processing (Spencer & O'Brien, 2006; Tsermentseli, O'Brien, & Spencer, 2008; see also Grinter, Maybery, & Badcock, 2010, for review). It is therefore important to determine whether the unexpected finding of increased integration of direction information in children with autism (Chapter 5) can be generalised to static tasks, such as orientation integration (Dakin, 2001) or size integration (Tibber et al., 2014). More generally, it would be interesting to determine whether the ability to integrate information about a single cue relates to the ability to integrate information across cues and across modalities in childhood (e.g. Gori et al., 2008; Nardini et al., 2008, 2010). Individuals with autism have been shown to integrate multimodal information over a greater temporal window than TD individuals (Foss-Feig et al., 2010; Stevenson et al., 2014), and future research might therefore investigate whether this increased integration relates to the direction integration results reported in Chapter 5.

7.7.2 Uncovering the mechanisms behind atypical motion processing in autism

Some accounts applied to motion processing in autism, such as WCC and EPF accounts, are essentially descriptive and do not offer a mechanistic explanation for *why* motion processing is atypical in autism. Pellicano and Burr's (2012) theory is therefore promising, as it suggests a mechanism for altered sensation and perception in autism, in the form of attenuated priors. However, to investigate whether this theory can account for motion processing in autism, it is important to design informative experiments. One hypothesis arising from Pellicano and Burr's account is that children with autism would show reduced adaptation to motion information, as reflected by a reduced motion after-effect. A second hypothesis is that the motion processing of children with autism is less biased than that of TD children. To test this, it could be investigated whether children with autism show a prior for slow motion (Weiss et al., 2002) and for smooth motion (Verghese & McKee, 2006) to the same extent as TD children.

Chapter 5 presented the unexpected finding that children with autism can average across more local motion signals than TD children. However, as noted in Section 4.2.6.1, the equivalent noise paradigm gives an estimate of the *effective* number of local motion directions that are globally pooled, and does not tell us what strategies children are using to perform the task. It is possible that children with autism weight local motion directions differently to TD children when making direction judgments. Powerful reverse correlation techniques could be used to determine which directions children with autism and TD children use to make their decisions.

As well as aiming to extend our understanding of increased motion integration in autism, it is also necessary to investigate segregation abilities in autism further. The equivalent noise direction integration task could be used with a pedestal of random incoherent noise, to see whether children with autism still show enhanced averaging when they have to ignore random noise. Partial cueing techniques could also be used, to determine whether children with autism can exclude task-irrelevant information when making motion coherence judgments. Burr, Baldassi, Morrone, and Verghese (2009) manipulated the relevance of each of a set of random dot patches arranged around a circle and found that typical adults could exclude irrelevant information in order to integrate the informative patches. It is possible that informative cuing would have less of an effect in lowering the coherence thresholds of children with autism compared to those of TD children. Similar paradigms could be used to investigate the exclusion of noise in static tasks, as has been previously investigated in children with dyslexia (Roach & Hogben, 2007).

These behavioural tasks could be supplemented with an investigation into the neural correlates of motion integration and segregation in children with autism. One possible neural correlate of enhanced direction integration is increased extrastriate population receptive fields (Schwarzkopf et al., 2014), which has so far only been investigated in autistic adults. Thus it is important to determine whether *children* with autism also have larger extrastriate population receptive fields, and whether this relates to enhanced direction integration performance. Previous functional magnetic resonance imaging (fMRI) studies have suggested that signatures of atypical motion processing in autism are found in early visual areas, such as V1 (Brieber et al., 2010; C. E. Robertson et al., 2014). Feedback connections to early visual areas are important in segregating motion information (Sillito et al., 2006; Raudies & Neumann, 2010). It is therefore conceivable that atypical V1 activation is a correlate of atypical segregation abilities in individuals with autism. Brain recording techniques that have a high temporal resolution, such as electroencephalography (EEG) and magnetoencephalography

(MEG), have the potential to uncover the time course of atypical motion processing in children with autism and TD children.

7.7.3 Bridging the gap between performance in psychophysical tasks and everyday functioning

A final challenge for future research is to investigate how performance in psychophysical tasks, as reported in this thesis, relates to the everyday experiences of children with autism. Parents of children with autism report that their children have difficulties in processing speed-related information (Chapter 3), yet these children showed no impairments in the speed discrimination task presented in Chapter 2. It is possible that psychophysical task performance would be more directly related to *self-reported* difficulties in speed-related information. Yet there are considerable differences between the psychophysical task presented in Chapter 3 and everyday speed processing tasks. In real-world scenarios, there are many objects moving simultaneously, and therefore integration and segregation demands may be more pronounced.

Furthermore, in real-world tasks, it is not only important to process motion effectively, but also to organise appropriate responses – for example, children may need to initiate eye movements, avoid approaching objects, and direct reaches and grasps towards moving objects. It may be that children with autism have difficulties coordinating perceptual and motor systems in order to organise responses to moving stimuli. Future studies may therefore investigate the interaction between perceptual and motor systems, for example by investigating the relationship between sensitivity to speed and direction information and motor skills, or by testing oculomotor responses to moving stimuli under free-viewing conditions (as previously investigated in TD individuals [Gegenfurtner, Xing, Scott, & Hawken, 2003; Rasche & Gegenfurtner, 2009)], ageing adults [O'Connor, Margrain, & Freeman, 2010] and individuals with schizophrenia [Clementz et al., 2007; Hong et al., 2009]). The relationship between parent-reported speed perception and motor skills reported in Chapter 3 suggests that this is a worthwhile avenue for future research.

The use of more ecologically valid tasks may help to bridge the gap between experimental task performance and everyday functioning. Motion coherence tasks are not very realistic, as objects do not tend to move randomly in everyday life. Furthermore, real objects do not disappear spontaneously, as in limited lifetime dot stimuli. The equivalent noise direction integration task presented in Chapters 4 and 5 is possibly more ecologically valid, as objects follow a common overall direction but with variability. This type of motion might be similar to judging the overall movement of a flock of birds, leaves being blown by the wind, or a shoal of fish, for example. However, much of the motion information received at the retina results from eye, head and body movements. Therefore, optic flow tasks may be more informative for understanding real-world motion processing. Indeed, optic flow information has been shown to be important for controlling movements such as those involved in walking and playing sports (Bardy & Warren, 1997; Bruggeman, Zosh, & Warren, 2007; Warren, Kay, Zosh, Duchon, & Sahuc, 2001). Informative paradigms that have not yet been investigated in children with autism, to my knowledge, include the perception of heading information in optic flow displays (e.g., Warren & Hannon, 1988; Warren & Saunders, 1995) and the perception of slant from motion gradients (e.g., Braunstein, 1968; Meese, Harris & Freeman, 1995).

7.8 Conclusion

This thesis aimed to characterise better motion processing in children with autism, and in particular to address why children with autism have difficulties with some motion processing tasks, but not others. The studies contained within this thesis show that children with autism perform similarly to TD children in a speed discrimination task, and do not consistently demonstrate elevated thresholds in a motion coherence task. Most surprisingly, however, children with autism showed *enhanced* averaging of direction information. These findings are inconsistent with theoretical accounts that propose general, pervasive difficulties in motion processing in autism (e.g., the dorsal stream vulnerability account; Braddick et al., 2003) and those that propose weak global processing in autism (e.g., WCC; Frith & Happé, 1994). More nuanced accounts are therefore required to explain the complex pattern of motion processing abilities in children with autism. Specifically, I suggest that children with autism effectively integrate motion information, but might have difficulties with segregating signal from noise. This hypothesis is consistent with the increased perceptual capacity account (Remington et al., 2009, 2012) and the ‘hypopriors’ account (Pellicano & Burr, 2012) of autistic perception. Further research is needed to characterise the nature and mechanisms of atypical motion perception in autism and to investigate how atypical motion processing relates to the everyday lives of children with autism.

8 References

Abramov, I., Hainline, L., Turkel, J., Lemerise, E., Smith, H., Gordon, J., & Petry, S. (1984). Rocket-ship psychophysics: assessing visual functioning in young children. *Investigative Ophthalmology and Visual Science*, *25*(11), 1307-1315.

Adams, R. J., & Courage, M. L. (2002). Using a single test to measure human contrast sensitivity from early childhood to maturity. *Vision Research, 42*(9), 1205-1210.

Ahmed, I. J., Lewis, T. L., Ellemberg, D., & Maurer, D. (2005). Discrimination of speed in 5-year-olds and adults: are children up to speed? *Vision Research, 45*, 2129-2135.

Aleman, A., Bronk, E., Kessels, R. P. C., Koppeschaar, H. P. F., & van Honk, J. (2004). A single administration of testosterone improves visuospatial ability in young women. *Psychoneuroendocrinology, 29*(5), 612-617.

Allard, R., & Cavanagh, P. (2012). Different processing strategies underlie voluntary averaging in low and high noise. *Journal of Vision, 12*(11):6, 1-12.

Amaral, D. G., Schumann, C. M., & Nordahl, C. W. (2008). Neuroanatomy of autism. *Trends in Neurosciences, 31*(3), 137-145.

American Psychiatric Association (2000). *Diagnostic and Statistical Manual of Mental Disorders: DSM-IV-TR (4th ed., Text Revision)*. Washington, DC: American Psychiatric Association.

American Psychiatric Association (2013). *Diagnostic and Statistical Manual of Mental Disorders (5th ed.)*. Arlington, VA: American Pyschiatric Publishing.

American Psychological Association Task Force on Socioeconomic Status (2007). *Report of the APA Task Force on Socioeconomic Status.* Washington, DC: American Psychological Association.

Ames, C., & Fletcher-Watson, S. (2010). A review of methods in the study of attention in autism. *Developmental Review, 30*(1), 52-73.

Annaz, D., Campbell, R., Coleman, M., Milne, E., & Swettenham, J. (2012). Young children with autism spectrum disorder do not preferentially attend to biological motion. *Journal of Autism and Developmental Disorders, 42*(3), 401-408.

Annaz, D., Remington, A., Milne, E., Coleman, M., Campbell, R., Thomas, M., & Swettenham, J. (2010). Development of motion processing in children with autism. *Developmental Science, 13*(6), 826-838.

Antal, A., Nitsche, M. A., Kruse, W., Kincses, T. Z., Hoffmann, K.-P., & Paulus, W. (2004). Direct current stimulation over V5 enhances visuomotor coordination by improving motion perception in humans. *Journal of Cognitive Neuroscience, 16*(4), 521-527.

Arena, A., Hutchinson, C. V., & Shimozaki, S. S. (2012). The effects of age on the spatial and temporal integration of global motion. *Vision Research, 58*(0), 27-32.

Arena, A., Hutchinson, C. V., Shimozaki, S. S., & Long, M. D. (2013). Visual discrimination in noise: behavioural correlates of age-related cortical decline. *Behavioural Brain Research, 243*, 102-108.

Ascher, D., & Grzywacz, N. M. (2000). A Bayesian model for the measurement of visual velocity. *Vision Research, 40*, 3427-3434.

Ashburner, J., Ziviani, J., & Rodger, S. (2008). Sensory processing and classroom emotional, behavioral, and educational outcomes in children with autism spectrum disorder. *American Journal of Occupational Therapy, 62*(5), 564-573.

Aslin, R. N., & Shea, S. L. (1990). Velocity thresholds in human infants: implications for the perception of motion. *Developmental Psychology, 26*(4), 589-598.

Asperger, H. (1991). 'Autistic psychopathy' in childhood (U. Frith, Trans.). In U. Frith (Ed.), *Autism and Asperger Syndrome*. Cambridge, UK: Cambridge University Press.

Atkinson, A. P. (2009). Impaired recognition of emotions from body movements is associated with elevated motion coherence thresholds in autism spectrum disorders. *Neuropsychologia, 47*, 3023-3029.

Atkinson, J., Braddick, O., Rose, F. E., Searcy, Y. M., Wattam-Bell, J., & Bellugi, U. (2006). Dorsal-stream motion processing deficits persist into adulthood in Williams syndrome. *Neuropsychologia, 44*(5), 828-833.

Atkinson, J., King, J., Braddick, O., Nokes, L., Anker, S., & Braddick, F. (1997). A specific deficit of dorsal stream function in Williams' syndrome. *NeuroReport, 8*(8), 1919-1922.

Ausderau, K. K., Furlong, M., Sideris, J., Bulluck, J., Little, L. M., Watson, L. R., . . . Baranek, G. T. (2014). Sensory subtypes in children with autism spectrum disorder: latent profile transition analysis using a national survey of sensory features. *Journal of Child Psychology and Psychiatry, 55*(8), 935-944.

Auyeung, B., Knickmeyer, R., Ashwin, E., Taylor, K., Hackett, G., & Baron-Cohen, S. (2012). Effects of fetal testosterone on visuospatial ability. *Archives of Sexual Behavior, 41*(3), 571-581.

Bagby, M. S., Dickie, V. A., & Baranek, G. T. (2012). How sensory experiences of children with and without autism affect family occupations. *American Journal of Occupational Therapy, 66*(1), 78-86.

Baird, G., Simonoff, E., Pickles, A., Chandler, S., Loucas, T., Meldrum, D., & Charman, T. (2006). Prevalence of disorders of the autism spectrum in a population cohort of children in South Thames: the Special Needs and Autism Project (SNAP). *The Lancet, 368*(9531), 210-215.

Baranek, G. T., David, F. J., Poe, M. D., Stone, W. L., & Watson, L. R. (2006). Sensory Experiences Questionnaire: discriminating sensory features in young children with autism, developmental delays and typical development. *Journal of Child Psychology and Psychiatry, 47*(6), 591-601.

Baranek, G. T., Foster, L. G., & Berkson, G. (1997). Tactile defensiveness and stereotyped behaviors. *American Journal of Occupational Therapy, 51*(2), 91-95.

Baranek, G. T., Watson, L. R., Boyd, B. A., Poe, M. D., David, F. J., & McGuire, L. (2013). Hyporesponsiveness to social and nonsocial sensory stimuli in children with autism, children with developmental delays, and typically developing children. *Development and Psychopathology, 25*(2), 307-320.

Barbaro, J., & Dissanayake, C. (2009). Autism spectrum disorders in infancy and toddlerhood: a review of the evidence on early signs, early identification tools, and early diagnosis. *Journal of Developmental and Behavioral Pediatrics, 30*(5), 447-459.

Bardy, B. G., & Warren Jr, W. H. (1997). Visual control of braking in goal-directed action and sport. *Journal of Sports Sciences, 15*(6), 607-620.

Barger, B., Campbell, J., & McDonough, J. (2013). Prevalence and onset of regression within autism spectrum disorders: a meta-analytic review. *Journal of Autism and Developmental Disorders, 43*(4), 817-828.

Barlow, H., & Tripathy, S. P. (1997). Correspondence noise and signal pooling in the detection of coherent visual motion. *Journal of Neuroscience, 17*(20), 7954-7966.

Barlow, H. B. (1956). Retinal noise and absolute threshold. *Journal of the Optical Society of America, 46*(8), 634-639.

Baron-Cohen, S. (2002). The extreme male brain theory of autism. *Trends in Cognitive Sciences, 6*(6), 248-254.

Baron-Cohen, S., Auyeung, B., Nørgaard-Pedersen, B., Hougaard, D. M., Abdallah, M. W., Melgaard, L., . . . Lombardo, M. V. (2014). Elevated fetal steroidogenic activity in autism. *Molecular Psychiatry*. doi:10.1038/mp.2014.48

Baron-Cohen, S., & Hammer, J. (1997). Is autism an extreme form of the "male brain"? *Advances in Infancy Research, 11*, 193-218.

Baron-Cohen, S., Lutchmaya, S., & Knickmeyer, R. (2004). *Prenatal Testosterone in Mind: Amniotic Fluid Studies.* Cambridge, MA: MIT Press.

Baron-Cohen, S., Scott, F. J., Allison, C., Williams, J., Bolton, P., Matthews, F. E., & Brayne, C. (2009). Prevalence of autism-spectrum conditions: UK school-based population study. *British Journal of Psychiatry, 194*(6), 500-509.

Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., & Clubley, E. (2001). The autism-spectrum quotient (AQ): evidence from Asperger syndrome/high-functioning autism, males and females, scientists and mathematicians. *Journal of Autism and Developmental Disorders, 31*(1), 5-17.

Bauman, M. L., & Kemper, T. L. (2005). Neuroanatomic observations of the brain in autism: a review and future directions. *International Journal of Developmental Neuroscience, 23*(2), 183-187.

Bayerl, P., & Neumann, H. (2004). Disambiguating visual motion through contextual feedback modulation. *Neural Computation, 16*(10), 2041-2066.

Beck, J. M., Ma, W. J., Pitkow, X., Latham, P. E., & Pouget, A. (2012). Not noisy, just wrong: the role of suboptimal inference in behavioral variability. *Neuron, 74*(1), 30-39.

Begeer, S., Mandell, D., Wijnker-Holmes, B., Venderbosch, S., Rem, D., Stekelenburg, F., & Koot, H. (2013). Sex differences in the timing of identification among children and adults with autism spectrum disorders. *Journal of Autism and Developmental Disorders, 43*(5), 1151-1156.

Behrmann, M., Avidan, G., Leonard, G. L., Kimchi, R., Luna, B., Humphreys, K., & Minshew, N. (2006). Configural processing in autism and its relationship to face processing. *Neuropsychologia, 44*(1), 110-129.

Belmonte, M. K. (2005). Abnormal visual motion processing as a neural endophenotype of autism. *Cahiers de Psychologie Cognitive (Current Psychology of Cognition), 23*(1-2), 65-74.

Belmonte, M. K., Cook, E. H., Jr., Anderson, G. M., Rubenstein, J. L. R., Greenough, W. T., Beckel-Mitchener, A., . . . Tierney, E. (2004). Autism as a disorder of neural information processing: directions for research and targets for therapy. *Molecular Psychiatry, 9*(7), 646-663.

Ben-Sasson, A., Cermak, S. A., Orsmond, G. I., Tager-Flusberg, H., Carter, A. S., Kadlec, M. B., & Dunn, W. (2007). Extreme sensory modulation behaviors in toddlers with autism spectrum disorders. *American Journal of Occupational Therapy, 61*(5), 584.

Ben-Sasson, A., Hen, L., Fluss, R., Cermak, S. A., Engel-Yeger, B., & Gal, E. (2009). A meta-analysis of sensory modulation symptoms in individuals with autism spectrum disorders. *Journal of Autism and Developmental Disorders, 39*, 1-11.

Ben-Sasson, A., Soto, T. W., Martínez-Pedraza, F., & Carter, A. S. (2013). Early sensory over-responsivity in toddlers with autism spectrum disorders as a predictor of family impairment and parenting stress. *Journal of Child Psychology and Psychiatry, 54*(8), 846-853.

Bennett, E., & Heaton, P. (2012). Is talent in autism spectrum disorders associated with a specific cognitive and behavioural phenotype? *Journal of Autism and Developmental Disorders, 42*(12), 2739-2753.

Bertone, A., & Faubert, J. (2006). Demonstrations of decreased sensitivity to complex motion information not enough to propose an autism-specific neural etiology. *Journal of Autism and Developmental Disorders, 36*(1), 55-64.

Bertone, A., Mottron, L., & Faubert, J. (2005). Dissociating pathway- versus complexity- specific accounts of motion perception impairments in autism. *Cahiers de Psychologie Cognitive (Current Psychology of Cognition), 23*(1-2), 75-83.

Bertone, A., Mottron, L., Jelenic, P., & Faubert, J. (2003). Motion perception in autism: a “complex” issue. *Journal of Cognitive Neuroscience, 15*(2), 218-225.

Bertone, A., Mottron, L., Jelenic, P., & Faubert, J. (2005). Enhanced and diminished visuo-spatial information processing in autism depends on stimulus complexity. *Brain, 128*(10), 2430-2441.

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.

Bishop, D. V. M., & Norbury, C. F. (2002). Exploring the borderlands of autistic disorder and specific language impairment: a study using standardised diagnostic instruments. *Journal of Child Psychology and Psychiatry, 43*(7), 917-929.

Blake, R., Turner, L. M., Smoski, M. J., Pozdol, S. L., & Stone, W. L. (2003). Visual recognition of biological motion is impaired in children with autism. *Psychological Science, 14*(2), 151-157.

Blumenthal, E. J., Bosworth, R. G., & Dobkins, K. R. (2013). Fast development of global motion processing in human infants. *Journal of Vision, 13*(13), 1-13.

Bocheva, N., Angelova, D., & Stefanova, M. (2013). Age-related changes in fine motion direction discriminations. *Experimental Brain Research, 228*(3), 257-278.

Bogdašina, O. (2003). *Sensory Perceptual Issues in Autism and Asperger Syndrome: Different Sensory Experiences, Different Perceptual Worlds*. London, UK: Jessica Kingsley Publishers.

Bogfjellmo, L.-G., Bex, P. J., & Falkenberg, H. K. (2014). The development of global motion discrimination in school aged children. *Journal of Vision, 14*(2), 19, 1-12.

Bölte, S. (2014). Is autism curable? *Developmental Medicine & Child Neurology*, doi:10.1111/dmcn.12495.

Booth, A. E., Pinto, J., & Bertenthal, B. I. (2002). Perception of the symmetrical patterning of human gait by infants. *Developmental Psychology, 38*(4), 554.

Born, R. T., & Tootell, R. B. H. (1992). Segregation of global and local motion processing in primate middle temporal visual area. *Nature, 357*, 497-499.

Boucher, J., & Lewis, V. (1992). Unfamiliar face recognition in relatively able autistic children. *Journal of Child Psychology and Psychiatry, 33*(5), 843-859.

Bourgeron, T. (2009). A synaptic trek to autism. *Current Opinion in Neurobiology, 19*(2), 231-234.

Boyd, B. A., & Baranek, G. T. (2005). *Sensory Questionnaire*. Unpublished manuscript. University of North Carolina at Chapel Hill.

Boyd, B. A., Baranek, G. T., Sideris, J., Poe, M. D., Watson, L. R., Patten, E., & Miller, H. (2010). Sensory features and repetitive behaviors in children with autism and developmental delays. *Autism Research, 3*(2), 78-87.

Boyd, B. A., McBee, M., Holtzclaw, T., Baranek, G. T., & Bodfish, J. W. (2009). Relationships among repetitive behaviors, sensory features, and executive functions in high functioning autism. *Research in Autism Spectrum Disorders, 3,* 959-966.

Braddick, O., & Atkinson, J. (2011). Development of human visual function. *Vision Research, 51*(13), 1588-1609.

Braddick, O. J., Atkinson, J., & Wattam-Bell, J. (2003). Normal and anomalous development of visual motion processing: motion coherence and 'dorsal-stream vulnerability'. *Neuropsychologia, 41,* 1769-1784.

Braddick, O. J., Lin, M.-H., Atkinson, J., & Wattam-Bell, J. (1998). Motion coherence thresholds: effect of dot lifetime and comparison with form coherence *Perception, 27 (ECVP Abstract Supplement),* 199.

Braddick, O. J., O'Brien, J. M. D., Wattam-Bell, J., Atkinson, J., & Turner, R. (2001). Brain areas sensitive to coherent visual motion. *Perception, 30*(1), 61-72.

Braddick, O. J., O’Brien, J. M. D., Wattam-Bell, J., Atkinson, J., & Turner, R. (2000). Form and motion coherence activate independent, but not dorsal/ventral segregated, networks in the human brain. *Current Biology, 10*(12), 731-734.

Bradley, A., & Freeman, R. D. (1982). Contrast sensitivity in children. *Vision Research, 22*, 953-959.

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10,* 433-436.

Braunstein, M. L. (1968). Motion and texture as sources of slant information. *Journal of Experimental Psychology, 78*, 247-253.

Brieber, S., Herpertz-Dahlmann, B., Fink, G. R., Kamp-Becker, I., Remschmidt, H., & Konrad, K. (2010). Coherent motion processing in autism spectrum disorder (ASD): an fMRI study. *Neuropsychologia, 48*, 1644-1651.

Britten, K. H., Shadlen, M. N., Newsome, W. T., & Movshon, J. A. (1992). The analysis of visual motion: a comparison of neuronal and psychophysical performance. *Journal of Neuroscience, 12*(12), 4745-4765.

Brock, J. (2012). Alternative Bayesian accounts of autistic perception: comment on Pellicano and Burr. *Trends in Cognitive Science*, *16*(12), 573-574.

Brock, J. (2014, February 14). Autism and the average [Web log post]. Retrieved from http://crackingtheenigma.blogspot.co.uk/2014/02/autism-and-average.html.

Brock, J. O. N., Brown, C. C., Boucher, J., & Rippon, G. (2002). The temporal binding deficit hypothesis of autism. *Development and Psychopathology, 14*(2), 209-224.

Brown, L. (2011, November 30). Person-first language: why it matters (the significance of semantics) [Web log post]. Retrieved from http://www.thinkingautismguide.com/2011/11/person-first-language-why-it-matters.html.

Bruggeman, H., Zosh, W., & Warren, William H. (2007). Optic flow drives human visuo-locomotor adaptation. *Current Biology, 17*(23), 2035-2040.

Brugha, T. S., McManus, S., Bankart, J., Scott, F., Purdon, S., Smith, J., . . . Meltzer, H. (2011). Epidemiology of autism spectrum disorders in adults in the community in England. *Archives of General Psychiatry, 68*(5), 459-465.

Bunney, W. E., Jr., Hetrick, W. P., Bunney, B. G., Patterson, J. V., Jin, Y., Potkin, S. G., & Sandman, C. A. (1999). Structured Interview for Assessing Perceptual Anomalies (SIAPA). *Schizophrenia Bulletin, 25*(3), 577-592.

Burr, D., & Thompson, P. (2011). Motion psychophysics: 1985-2010. *Vision Research, 51*(13), 1431-1456.

Burr, D. C., Baldassi, S., Morrone, M. C., & Verghese, P. (2009). Pooling and segmenting motion signals. *Vision Research, 49*(10), 1065-1072.

Burr, D. C., Fiorentini, A., & Morrone, C. (1998). Reaction time to motion onset of luminance and chromatic gratings is determined by perceived speed. *Vision Research, 38*(23), 3681-3690.

Buss, E., Hall, J. W., 3rd, & Grose, J. H. (2006). Development and the role of internal noise in detection and discrimination thresholds with narrow band stimuli. *Journal of the Acoustical Society of America, 120*(5):1, 2777-2788.

Casanova, M. F., Buxhoeveden, D. P., Switala, A. E., & Roy, E. (2002). Minicolumnar pathology in autism. *Neurology, 58*(3), 428-432.

Cavanagh, P. (1992). Attention-based motion perception. *Science, 257*(5076), 1563-1565.

Celani, G., Battacchi, M. W., & Arcidiacono, L. (1999). The understanding of the emotional meaning of facial expressions in people with autism. *Journal of Autism and Developmental Disorders, 29*(1), 57-66.

Centers for Disease Control and Prevention (2007). Prevalence of autism spectrum disorders - Autism and Developmental Disabilities Monitoring Network, 6 Sites, United States, 2000. *MMWR Surveillance Summaries, 56*, 1-28.

Centers for Disease Control and Prevention (2012). Prevalence of autism spectrum disorders - Autism and Developmental Disabilities Monitoring Network, 14 Sites, United States, 2008. *MMWR Surveillance Summaries, 61*(3), 1-19.

Centers for Disease Control and Prevention (2014). Prevalence of autism spectrum disorders among children aged 8 years: autism and developmental disabilities monitoring network, 11 sites, United States, 2010. *MMWR Surveillance Summaries, 63*(2), 1-22.

Chandler, S., Charman, T., Baird, G., Simonoff, E., Loucas, T. O. M., Meldrum, D., . . . Pickles, A. (2007). Validation of the Social Communication Questionnaire in a population cohort of children with autism spectrum disorders. *Journal of the American Academy of Child and Adolescent Psychiatry, 46*(10), 1324-1332.

Charman, T. (2011). The highs and lows of counting autism. *American Journal of Psychiatry, 168*(9), 873-875.

Charman, T., Pickles, A., Simonoff, E., Chandler, S., Loucas, T., & Baird, G. (2011). IQ in children with autism spectrum disorders: data from the Special Needs and Autism Project (SNAP). *Psychological Medicine, 41*(3), 619.

Chawarska, K., Klin, A., & Volkmar, F. R. (Eds.). (2008). *Autism Spectrum Disorders in Infants and Toddlers: Diagnosis, Assessment, and Treatment*. New York: Guilford Press.

Chen, Y., Nakayama, K., Levy, D., Matthysse, S., & Holzman, P. (2003). Processing of global, but not local, motion direction is deficient in schizophrenia. *Schizophrenia Research, 61*(2-3), 215-227.

Chen, Y., Norton, D., & McBain, R. (2014). Effects of domain-specific noise on visual motion processing in schizophrenia. *PLoS One, 9*(6), e99031.

Chen, Y., Norton, D. J., McBain, R., Gold, J., Frazier, J. A., & Coyle, J. T. (2012). Enhanced local processing of dynamic visual information in autism: evidence from speed discrimination. *Neuropsychologia*, *50,* 733-739.

Cheng, K., Hasegawa, T., Saleem, K. S., & Tanaka, K. (1994). Comparison of neuronal selectivity for stimulus speed, length, and contrast in the prestriate visual cortical areas V4 and MT of the macaque monkey. *Journal of Neurophysiology, 71*(6), 2269-2280.

Cheng, Y., Chou, K.-H., Chen, I. Y., Fan, Y.-T., Decety, J., & Lin, C.-P. (2010). Atypical development of white matter microstructure in adolescents with autism spectrum disorders. *NeuroImage, 50*(3), 873-882.

Chevallier, C., Kohls, G., Troiani, V., Brodkin, E. S., & Schultz, R. T. (2012). The social motivation theory of autism. *Trends in Cognitive Sciences, 16*(4), 231-239.

Clementz, B. A., McDowell, J. E., & Dobkins, K. R. (2007). Compromised speed discrimination among schizophrenia patients when viewing smooth pursuit targets. *Schizophrenia Research, 95,* 61-64.

Conners, C. K., Sitarenios, G., Parker, J. D. A., & Epstein, J. N. (1998). The revised Conners' Parent Rating Scale (CPRS-R): factor structure, reliability, and criterion validity. *Journal of Abnormal Child Psychology, 26*(4), 257-268.

Constantino, J., Davis, S., Todd, R., Schindler, M., Gross, M., Brophy, S., . . . Reich, W. (2003). Validation of a brief quantitative measure of autistic traits: comparison of the Social Responsiveness Scale with the Autism Diagnostic Interview-Revised. *Journal of Autism and Developmental Disorders, 33*(4), 427-433.

Constantino, J. N., & Todd, R. D. (2003). Autistic traits in the general population: a twin study. *Archives of General Psychiatry, 60*(5), 524-530.

Constantino, J. N., Zhang, Y., Frazier, T., Abbacchi, A. M., & Law, P. (2010). Sibling recurrence and the genetic epidemiology of autism. *American Journal of Psychiatry, 167*(11), 1349-1356.

Corbetta, M., Miezin, F. M., Dobmeyer, S., Shulman, G. L., & Peterson, S. E. (1991). Selective and divided attention during visual discriminations of shape, color and speed: functional anatomy by Positron Emission Tomography. *Journal of Neuroscience, 11*(8), 2383-2402.

Corsello, C., Hus, V., Pickles, A., Risi, S., Cook, E. H., Leventhal, B. L., & Lord, C. (2007). Between a ROC and a hard place: decision making and making decisions about using the SCQ. *Journal of Child Psychology and Psychiatry, 48*(9), 932-940.

Courchesne, E., Karns, C. M., Davis, H. R., Ziccardi, R., Carper, R. A., Tigue, Z. D., . . . Lord, C. (2001). Unusual brain growth patterns in early life in patients with autistic disorder: an MRI study. *Neurology, 57*(2), 245-254.

Courchesne, E., & Pierce, K. (2005). Why the frontal cortex in autism might be talking only to itself: local over-connectivity but long-distance disconnection. *Current Opinion in Neurobiology, 15*(2), 225-230.

Dakin, S., & Frith, U. (2005). Vagaries of visual perception in autism. *Neuron, 48*, 497-507.

Dakin, S. C. (2001). Information limit on the spatial integration of local orientation signals. *Journal of the Optical Society of America A, 18*(5), 1016-1026.

Dakin, S. C., Mareschal, I., & Bex, P. J. (2005). Local and global limitations on direction integration assessed using equivalent noise analysis. *Vision Research, 45*(24), 3027-3049.

Davis, G., & Plaisted-Grant, K. (in press). Low endogenous neural noise in autism. *Autism*.

Davis, R. A. O., Bockbrader, M. A., Murphy, R. R., Hetrick, W. P., & O'Donnell, B. F. (2006). Subjective perceptual distortions and visual dysfunction in children with autism. *Journal of Autism and Developmental Disorders, 36*(2), 199-210.

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.

de-Wit, L., & Wagemans, J. (in press). Individual differences in local and global perceptual organization. In J. Wagemans (Ed.), *Oxford Handbook of Perceptual Organization*. Oxford, UK: Oxford University Press.

de Bruyn, B., & Orban, G. A. (1988). Human velocity and direction discrimination measured with random dot patterns. *Vision Research, 28*(12), 1323-1335.

de Haan, E. H. F., & Cowey, A. (2011). On the usefulness of 'what' and 'where' pathways in vision. *Trends in Cognitive Sciences, 15*(10), 460-466.

de Jonge, M. V., Kemner, C., de Haan, E. H., Coppens, J. E., van den Berg, T. J. T. P., & van Engeland, H. (2007). Visual information processing in high-functioning individuals with autism spectrum disorders and their parents. *Neuropsychology, 21*(1), 65-73.

Del Viva, M. M., Igliozzi, R., Tancredi, R., & Brizzolara, D. (2006). Spatial and motion integration in children with autism. *Vision Research, 46*(8-9), 1242-1252.

Delaney, H. D., & Maxwell, S. E. (1981). On using analysis of covariance in repeated measures designs. *Multivariate Behavioral Research, 16*(1), 105-123.

Demb, J. B., Boynton, G. M., Best, M., & Heeger, D. J. (1998). Psychophysical evidence for a magnocellular pathway deficit in dyslexia. *Vision Research, 38*, 1555-1559.

Dinstein, I., Heeger, David J., Lorenzi, L., Minshew, Nancy J., Malach, R., & Behrmann, M. (2012). Unreliable evoked responses in autism. *Neuron, 75*(6), 981-991.

Distler, C., Bachevalier, J., Kennedy, C., Mishkin, M., & Ungerleider, L. G. (1996). Functional development of the corticocortical pathway for motion analysis in the macaque monkey: a 14C-2-deoxyglucose study. *Cerebral Cortex, 6*(2), 184-195.

Donkers, F. L., Schipul, S., Baranek, G., Cleary, K., Willoughby, M., Evans, A., . . . Belger, A. (2013). Attenuated auditory event-related potentials and associations with atypical sensory response patterns in children with autism. *Journal of Autism and Developmental Disorders*, doi:10.1007/s10803-013-1948-y.

Dosher, B. A., & Lu, Z.-L. (2000). Noise exclusion in spatial attention. *Psychological Science, 11*(2), 139-145.

Duffy, C. J., & Wurtz, R. H. (1997). Medial superior temporal area neurons respond to speed patterns in optic flow. *Journal of Neuroscience, 17*(8), 2839-2851.

Dunn, W. (1999). *Sensory Profile: User's Manual*. San Antonio, TX: The Psychological Corporation.

Edwards, M., Badcock, D. R., & Smith, A. T. (1998). Independent speed-tuned global-motion systems. *Vision Research, 38*, 1573-1580.

Edwards, V. T., Giaschi, D. E., Dougherty, R. F., Edgell, D., Bjornson, B. H., Lyons, C., & Douglas, R. M. (2004). Psychophysical indexes of temporal processing abnormalities in children with developmental dyslexia. *Developmental Neuropsychology, 25*(3), 321-354.

Efron, B., & Tibshirani, R. (1993). *An Introduction to the Bootstrap*. New York: Chapman & Hall.

Ellemberg, D., Lewis, T. L., Dirks, M., Maurer, D., Ledgeway, T., Guillemot, J. P., & Lepore, F. (2004). Putting order into the development of sensitivity to global motion. *Vision Research, 44*(20), 2403-2411.

Ellemberg, D., Lewis, T. L., Liu, C. H., & Maurer, D. (1999). Development of spatial and temporal vision during childhood. *Vision Research, 39*, 2325-2333.

Ellemberg, D., Lewis, T. L., Maurer, D., Lee, B., Ledgeway, T., Guilemot, J. P., & Lepore, F. (2010). The effect of displacement on sensitivity to first-and second-order global motion in 5-year-olds and adults. *Seeing and Perceiving, 23*(5-6), 5-6.

Elsabbagh, M., Divan, G., Koh, Y.-J., Kim, Y. S., Kauchali, S., Marcín, C., . . . Fombonne, E. (2012). Global prevalence of autism and other pervasive developmental disorders. *Autism Research, 5*(3), 160-179.

Evers, K., de-Wit, L., Hallen, R., Haesen, B., Steyaert, J., Noens, I., & Wagemans, J. (2014). Reduced grouping interference in children with ASD: evidence from a multiple object tracking task. *Journal of Autism and Developmental Disorders*, doi:10.1007/s10803-013-2031-4.

Faisal, A. A., Selen, L. P. J., & Wolpert, D. M. (2008). Noise in the nervous system. *Nature Reviews Neuroscience, 9*(4), 292-303.

Falkenberg, H. K., & Bex, P. J. (2007). Sources of motion-sensitivity loss in glaucoma. *Investigative Ophthalmology and Visual Science, 48*(6), 2913-2921.

Falkenberg, H. K., Simpson, W. A., & Dutton, G. N. (2014). Development of sampling efficiency and internal noise in motion detection and discrimination in school-aged children. *Vision Research, 100*, 8-17.

Falter, C. M., Arroyo, M., & Davis, G. J. (2006). Testosterone: activation or organization of spatial cognition? *Biological Psychology, 73*(2), 132-140.

Falter, C. M., Plaisted, K. C., & Davis, G. (2008). Visuo-spatial processing in autism: testing the predictions of extreme male brain theory. *Journal of Autism and Developmental Disorders*, *38*(3), 507-515.

Fesi, J. D., Thomas, A. L., & Gilmore, R. O. (2014). Cortical responses to optic flow and motion contrast across patterns and speeds. *Vision Research, 100*, 56-71.

Festa, E. K., & Welch, L. (1997). Recruitment mechanisms in speed and fine-direction discrimination tasks. *Vision Research, 37*(22), 3129-3143.

Field, A. (2005). *Discovering Statistics Using SPSS (2nd ed.)*. London: Sage Publications.

Flechsig, P. (1901). Developmental (myelogenetic) localisation of the cerebral cortex in the human subject. *The Lancet*, *2*, 1027-1029.

Fombonne, E. (2005). Epidemiological studies of pervasive developmental disorders. In F. R. Volkmar, A. Klin, R. Paul & D. J. Cohen (Eds.), *Handbook of Autism and Pervasive Developmental Disorders (3rd ed.)*. Hoboken, NJ: Wiley.

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.

Foss-Feig, J. H., Tadin, D., Schauder, K. B., & Cascio, C. J. (2013). A substantial and unexpected enhancement of motion perception in autism. *Journal of Neuroscience, 33*(19), 8243-8249.

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.

Fox, M. D., Snyder, A. Z., Vincent, J. L., & Raichle, M. E. (2007). Intrinsic fluctuations within cortical systems account for intertrial variability in human behavior. *Neuron, 56*(1), 171-184.

Fox, R., & McDaniel, C. (1982). The perception of biological motion by human infants. *Science, 218*(4571), 486-487.

Franklin, A., Sowden, P., Burley, R., Notman, L., & Alder, E. (2008). Color perception in children with autism. *Journal of Autism and Developmental Disorders, 38*(10), 1837-1847.

Franklin, A., Sowden, P., Notman, L., Gonzalez-Dixon, M., West, D., Alexander, I., . . . White, A. (2010). Reduced chromatic discrimination in children with autism spectrum disorders. *Developmental Science, 13*(1), 188-200.

Freitag, C. M., Konrad, C., Häberlen, M., Kleser, C., von Gontard, A., Reith, W., . . . Krick, C. (2008). Perception of biological motion in autism spectrum disorders. *Neuropsychologia, 46*(5), 1480-1494.

Frith, U. (1989). *Autism: Explaining the Enigma*. Oxford UK: Basil Blackwell

Frith, U., & Happé, F. (1994). Autism: beyond “theory of mind”. *Cognition, 50*(1–3), 115-132.

Garber, K. (2007). Neuroscience: autism's cause may reside in abnormalities at the synapse. *Science, 317*(5835), 190.

Garey, L. J., & De Courten, C. (1983). Structural development of the lateral geniculate nucleus and visual cortex in monkey and man. *Behavioural Brain Research, 10*(1), 3-13.

Gegenfurtner, K. R., & Hawken, M. J. (1996). Interaction of motion and color in the visual pathways. *Trends in Neurosciences, 19*(9), 394-401.

Gegenfurtner, K. R., Xing, D., Scott, B. H., & Hawken, M. J. (2003). A comparison of pursuit eye movement and perceptual performance in speed discrimination. *Journal of Vision, 3,* 865-876.

Gepner, B., Deruelle, C., & Grynfeltt, S. (2001). Motion and emotion: a novel approach to the study of face processing by young autistic children. *Journal of Autism and Developmental Disorders, 31*(1), 37-45.

Gepner, B., & Féron, F. (2009). Autism: a world changing too fast for a mis-wired brain? *Neuroscience and Biobehavioral Reviews, 33*, 1227-1242.

Gepner, B., Lainé, F., & Tardif, C. (2005). E-motion mis-sight and other temporal processing disorders in autism. *Cahiers de Psychologie Cognitive/Current Psychology of Cognition, 23*, 104-121.

Gepner, B., Lainé, F., & Tardif, C. (2010). Désordres de la constellation autistique : un monde trop rapide pour un cerveau disconnecté ? *Psychiatrie, Sciences Humaines, Neurosciences (PSN). 8*(2), 67-76.

Gepner, B., Mestre, D., Masson, G., & de Schonen, S. (1995). Postural effects of motion vision in young autistic children. *NeuroReport*, *6*(8), 1211-1214.

Gepner, B., & Mestre, D. R. (2002). Postural reactivity to fast visual motion differentiates autistic from children with Asperger syndrome. *Journal of Autism and Developmental Disorders, 32*(3), 231-238.

Gernsbacher, M. A., Dawson, M., & Hill Goldsmith, H. (2005). Three reasons not to believe in an autism epidemic. *Current Directions in Psychological Science, 14*(2), 55-58.

Gerrard, S., & Rugg, G. (2009). Sensory impairments and autism: a re-examination of causal modelling. *Journal of Autism and Developmental Disorders, 39,* 1449-1463.

Geschwind, D. H., & Levitt, P. (2007). Autism spectrum disorders: developmental disconnection syndromes. *Current Opinion in Neurobiology, 17*(1), 103-111.

Gibson, L. Y., Hogben, J. H., & Fletcher, J. (2006). Visual and auditory processing and component reading skills in developmental dyslexia. *Cognitive Neuropsychology, 23*(4), 621-642.

Gilmore, R. O., Hou, C., Pettet, M. W., & Norcia, A. M. (2007). Development of cortical responses to optic flow. *Visual Neuroscience, 24*(6), 845-856.

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., . . . Toga, A. W. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Sciences of the United States of America, 101*(21), 8174-8179.

Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences, 15*(1), 20-25.

Goodbourn, P. T., Bosten, J. M., Hogg, R. E., Bargary, G., Lawrance-Owen, A. J., & Mollon, J. D. (2012). Do different 'magnocellular tasks' probe the same neural substrate? *Proceedings of the Royal Society B, 279*, 4263-4271.

Gori, M., Del Viva, M., Sandini, G., & Burr, D. C. (2008). Young children do not integrate visual and haptic form information. *Current Biology, 18*(9), 694-698.

Gotham, K., Risi, S., Dawson, G., Tager-Flusberg, H., Joseph, R., Carter, A., . . . Hyman, S. L. (2008). A replication of the Autism Diagnostic Observation Schedule (ADOS) revised algorithms. *Journal of the American Academy of Child and Adolescent Psychiatry, 47*(6), 642-651.

Gotham, K., Risi, S., Pickles, A., & Lord, C. (2007). The Autism Diagnostic Observation Schedule: revised algorithms for improved diagnostic validity. *Journal of Autism and Developmental Disorders, 37*(4), 613-627.

Grabrucker, A. M. (2013). Environmental factors in autism. *Frontiers in Psychiatry, 3*(118), 1-13.

Grandin, T. (1995). *Thinking in Pictures and Other Reports from my Life with Autism*. New York: Doubleday.

Green, D. M., & Swets, J. A. (1966). *Signal Detection Theory and Psychophysics*. New York: Wiley.

Green, S., Ben-Sasson, A., Soto, T., & Carter, A. (2012). Anxiety and sensory over-responsivity in toddlers with autism spectrum disorders: bidirectional effects across time. *Journal of Autism and Developmental Disorders, 42*(6), 1112-1119.

Green, S. A., Rudie, J. D., Colich, N. L., Wood, J. J., Shirinyan, D., Hernandez, L., . . . Bookheimer, S. Y. (2013). Overreactive brain responses to sensory stimuli in youth With autism spectrum disorders. *Journal of the American Academy of Child and Adolescent Psychiatry, 52*(11), 1158-1172.

Greenaway, R., Davis, G., & Plaisted-Grant, K. (2013). Marked selective impairment in autism on an index of magnocellular function. *Neuropsychologia, 51*(4), 592-600.

Greenaway, R., & Plaisted, K. (2005). Top-down attentional modulation in autistic spectrum disorders is stimulus-specific. *Psychological Science, 16*(12), 987-994.

Greffou, S., Bertone, A., Hahler, E.-M., Hanssens, J.-M., Mottron, L., & Faubert, J. (2012). Postural hypo-reactivity in autism is contingent on development and visual environment: a fully immersive virtual reality study. *Journal of Autism and Developmental Disorders, 42*(6), 961-970.

Gregory, B. L., & Plaisted-Grant, K. C. (2013). The Autism-Spectrum Quotient and visual search: shallow and deep autistic endophenotypes. *Journal of Autism and Developmental Disorders,* doi:10.1007/s10803-013-1951-3.

Greimel, E., Bartling, J., Dunkel, J., Brückl, M., Deimel, W., Remschmidt, H., . . . Schulte-Körne, G. (2013). The temporal dynamics of coherent motion processing in autism spectrum disorder: evidence for a deficit in the dorsal pathway. *Behavioural Brain Research, 251*, 168-175.

Grinter, E. J., Maybery, M. T., & Badcock, D. R. (2010). Vision in developmental disorders: is there a dorsal stream deficit? *Brain Research Bulletin, 82*, 147-160.

Grinter, E. J., Maybery, M. T., Pellicano, E., Badcock, J. C., & Badcock, D. R. (2010). Perception of shapes targeting local and global processes in autism spectrum disorders. *Journal of Child Psychology and Psychiatry, 51*(6), 717-724.

Grinter, E. J., Maybery, M. T., van Beek, P. L., Pellicano, E., Badcock, J. C., & Badcock, D. R. (2009). Global visual processing and self-rated autistic-like traits. *Journal of Autism and Developmental Disorders, 39*, 1278-1290.

Grzadzinski, R., Huerta, M., & Lord, C. (2013). DSM-5 and autism spectrum disorders (ASDs): an opportunity for identifying ASD subtypes. *Molecular Autism, 4*(1), 1-6.

Gunn, A., Cory, E., Atkinson, J., Braddick, O., Wattam-Bell, J., Guzzetta, A., & Cioni, G. (2002). Dorsal and ventral stream sensitivity in normal development and hemiplegia. *NeuroReport, 13*(6), 843-847.

Hadad, B.-S., Maurer, D., & Lewis, T. L. (2011). Long trajectory for the development of sensitivity to global and biological motion. *Developmental Science, 14*(6), 1330-1339.

Hadjikhani, N., Joseph, R. M., Snyder, J., & Tager-Flusberg, H. (2006). Anatomical differences in the mirror neuron system and social cognition network in autism. *Cerebral Cortex, 16*(9), 1276-1282.

Hallmayer, J., Cleveland, S., Torres, A., Phillips, J., Cohen, B., Torigoe, T., . . . Risch, N. (2011). Genetic heritability and shared environmental factors among twin pairs with autism. *Archives of General Psychiatry, 68*(11), 1095-1102.

Hammett, S. T., Champion, R. A., Morland, A. B., & Thompson, P. G. (2005). A ratio model of perceived speed in the human visual system. *Proceedings of the Royal Society B: Biological Sciences, 272*(1579), 2351-2356.

Hansen, P. C., Stein, J. F., Orde, S. R., Winter, J. L., & Talcott, J. B. (2001). Are dyslexics' visual deficits limited to measures of dorsal stream function? *NeuroReport, 12*(7), 1527-1530.

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. G. E., & Booth, R. D. L. (2008). The power of the positive: revisiting weak coherence in autism spectrum disorders. *Quarterly Journal of Experimental Psychology, 61*(1), 50-63.

Hardan, A., Muddasani, S., Vemulapalli, M., Keshavan, M., & Minshew, N. (2006). An MRI study of increased cortical thickness in autism. *American Journal of Psychiatry, 163*(7), 1290-1292.

Hatta, S., Kumagami, T., Qian, J., Thornton, M., Smith, E. L., & Chino, Y. M. (1998). Nasotemporal directional bias of V1 neurons in young infant monkeys. *Investigative Ophthalmology and Visual Science, 39*(12), 2259-2267.

Hayward, J., Truong, G., Partanen, M., & Giaschi, D. (2011). Effects of speed, age, and amblyopia on the perception of motion-defined form. *Vision Research, 51*(20), 2216-2223.

Head, A. M., McGillivray, J. A., & Stokes, M. A. (2014). Gender differences in emotionality and sociability in children with autism spectrum disorders. *Molecular Autism, 5*(1), 1-9.

Heaton, P., Ludlow, A., & Roberson, D. (2008). When less is more: poor discrimination but good colour memory in autism. *Research in Autism Spectrum Disorders, 2*(1), 147-156.

Henderson, S. E., Sugden, D. A., & Barnett, A. L. (2007). *Movement Assessment Battery for Children-2 (Movement ABC-2): Examiner's Manual*. London UK: Pearson.

Herrington, J. D., Baron-Cohen, S., Wheelwright, S. J., Singh, K. D., Bullmore, E. T., Brammer, M., & Williams, S. C. R. (2007). The role of MT+/V5 during biological motion perception in Asperger Syndrome: an fMRI study. *Research in Autism Spectrum Disorders, 1*(1), 14-27.

Hess, R. F., Mansouri, B., Dakin, S. C., & Allen, H. A. (2006). Integration of local motion is normal in amblyopia. *Journal of the Optical Society of America A, 23*(5), 986-992.

Hiller, R. M., Young, R. L., & Weber, N. (2014). Sex differences in autism spectrum disorder based on DSM-5 criteria: evidence from clinician and teacher reporting. *Journal of Abnormal Child Psychology*, doi:10.1007/s10802-014-9881-x.

Hilton, C., Graver, K., & LaVesser, P. (2007). Relationship between social competence and sensory processing in children with high functioning autism spectrum disorders. *Research in Autism Spectrum Disorders, 1*(2), 164-173.

Hilton, C. L., Harper, J. D., Kueker, R. H., Lang, A. R., Abbacchi, A. M., Todorov, A., & LaVesser, P. D. (2010). Sensory responsiveness as a predictor of social severity in children with High Functioning Autism Spectrum Disorders. *Journal of Autism and Developmental Disorders, 40*, 937-945.

Hilton, C. L., Zhang, Y., Whilte, M. R., Klohr, C. L., & Constantino, J. (2012). Motor impairment in sibling pairs concordant and discordant for autism spectrum disorders. *Autism, 16*(4), 430-441.

Hiris, E., & Blake, R. (1995). Discrimination of coherent motion when local motion varies in speed and direction. *Journal of Experimental Psychology: Human Perception and Performance, 21*(2), 308-317.

Hirshkowitz, A., & Wilcox, T. (2013). Infants' ability to extract three-dimensional shape from coherent motion. *Infant Behavior and Development, 36*(4), 863-872.

Hong, L. E., Turano, K. A., O'Neill, H. B., Hao, L., Wonodi, I., McMahon, R. P., & Thaker, G. K. (2009). Is motion-perception deficit in schizophrenia a consequence of eye-tracking abnormality? *Biological Psychiatry, 65*, 1079-1085.

Hou, C., Gilmore, R. O., Pettet, M. W., & Norcia, A. M. (2009). Spatio-temporal tuning of coherent motion evoked responses in 4–6 month old infants and adults. *Vision Research, 49*(20), 2509-2517.

Howlin, P., Goode, S., Hutton, J., & Rutter, M. (2009). Savant skills in autism: psychometric approaches and parental reports. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1522), 1359-1367.

Hubel, D. H., & Wiesel, T. N. (1962). Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *Journal of Physiology, 160*(1), 106-154.

Hubert, B., Wicker, B., Moore, D. G., Monfardini, E., Duverger, H., Da Fonseca, D., & Deruelle, C. (2007). Recognition of emotional and non-emotional biological motion in individuals with autistic spectrum disorders. *Journal of Autism and Developmental Disorders, 37*(7), 1386-1392.

Huk, A. C., & Heeger, D. J. (2000). Task-related modulation of visual cortex. *Journal of Neurophysiology, 83*(6), 3525-3536.

Humphreys, K., Minshew, N., Leonard, G. L., & Behrmann, M. (2007). A fine-grained analysis of facial expression processing in high-functioning adults with autism. *Neuropsychologia, 45*(4), 685-695.

Hupe, J. M., James, A. C., Payne, B. R., Lomber, S. G., Girard, P., & Bullier, J. (1998). Cortical feedback improves discrimination between figure and background by V1, V2 and V3 neurons. *Nature, 394*(6695), 784-787.

Hutcheson, G., & Sofroniou, N. (1999). *The Multivariate Social Scientist*. London: Sage Publications.

Huttenlocher, P. R., & de Courten, C. (1987). The development of synapses in striate cortex of man. *Human Neurobiology, 6*(1), 1-9.

Huttenlocher, P. R., de Courten, C., Garey, L. J., & Van der Loos, H. (1982). Synaptogenesis in human visual cortex: evidence for synapse elimination during normal development. *Neuroscience Letters, 33*(3), 247-252.

Hyde, K. L., Samson, F., Evans, A. C., & Mottron, L. (2010). Neuroanatomical differences in brain areas implicated in perceptual and other core features of autism revealed by cortical thickness analysis and voxel-based morphometry. *Human Brain Mapping, 31*(4), 556-566.

Ivry, R. B., & Diener, H. C. (1991). Impaired velocity perception in patients with lesions of the cerebellum. *Journal of Cognitive Neuroscience, 3*(4), 355-366.

Jackson, B. L., Blackwood, E. M., Blum, J., Carruthers, S. P., Nemorin, S., Pryor, B. A., . . . Crewther, D. P. (2013). Magno- and parvocellular contrast responses in varying degrees of autistic trait. *PLoS One, 8*(6), e66797.

Jarrold, C., & Brock, J. (2004). To match or not to match? Methodological issues in autism-related research. *Journal of Autism and Developmental Disorders, 34*(1), 81-86.

Jasmin, E., Couture, M., McKinley, P., Reid, G., Fombonne, E., & Gisel, E. (2009). Sensori-motor and daily living skills of preschool children with autism spectrum disorders. *Journal of Autism and Developmental Disorders, 39*(2), 231-241.

Jeste, S. S., & Geschwind, D. H. (2014). Disentangling the heterogeneity of autism spectrum disorder through genetic findings. *Nature Reviews Neurology, 10,* 74-81.

Jolliffe, T., & Baron-Cohen, S. (1997). Are people with autism and Asperger syndrome faster than normal on the Embedded Figures test? *Journal of Child Psychology and Psychiatry, 38*(5), 527-534.

Jones, C. R. G., Swettenham, J., Charman, T., Marsden, A. J. S., Tregay, J., Baird, G., . . . Happé, F. (2011). No evidence for a fundamental visual motion processing deficit in adolescents with autism spectrum disorders. *Autism Research, 4*, 347-357.

Jones, E. J., Gliga, T., Bedford, R., Charman, T., & Johnson, M. H. (2014). Developmental pathways to autism: a review of prospective studies of infants at risk. *Neuroscience and Biobehavioral Reviews, 39,* 1-33.

Jones, R., Quigney, C., & Huws, J. (2003). First-hand accounts of sensory perceptual experiences in autism: a qualitative analysis. *Journal of Intellectual and Developmental Disability, 28*(2), 112-121.

Kaiser, H. F. (1960). The application of electronic computers to factor analysis. *Educational and Psychological Measurement, 20*, 141-151.

Kaiser, H. F. (1974). An index of factorial simplicity. *Psychometrika, 39*, 31-36.

Kaiser, M., & Shiffrar, M. (2009). The visual perception of motion by observers with autism spectrum disorders: a review and synthesis. *Psychonomic Bulletin and Review, 16*(5), 761-777.

Kaldy, Z., Kraper, C., Carter, A. S., & Blaser, E. (2011). Toddlers with autism spectrum disorder are more successful at visual search than typically developing toddlers. *Developmental Science, 14*(5), 980-988.

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

Karmiloff-Smith, A. (2009). Nativism versus neuroconstructivism: rethinking the study of developmental disorders. *Developmental Psychology, 45*(1), 56-63.

Keehn, B., Wagner, J. B., Tager-Flusberg, H., & Nelson, C. A. (2013). Functional connectivity in the first year of life in infants at-risk for autism: a preliminary near-infrared spectroscopy study. *Frontiers in Human Neuroscience, 7*(444), 1-10.

Keller, T. A., Kana, R. K., & Just, M. A. (2007). A developmental study of the structural integrity of white matter in autism. *NeuroReport, 18,* 23-27.

Kemner, C., van Ewijk, L., van Engeland, H., & Hooge, I. (2008). Eye movements during visual search tasks indicate enhanced stimulus discriminability in subjects with PDD. *Journal of Autism and Developmental Disorders, 38*(3), 553-557.

Kern, J. K., Trivedi, M. H., Grannemann, B. D., Garver, C. R., Johnson, D. G., Andrews, A. A., . . . Schroeder, J. L. (2007). Sensory correlations in autism. *Autism, 11*(2), 123-134.

Kim, Y. S., Leventhal, B. L., Koh, Y. J., Fombonne, E., Laska, E., Lim, E. C., . . . Grinker, R. R. (2011). Prevalence of autism spectrum disorders in a total population sample. *American Journal of Psychiatry, 168*(9), 904-912.

Kingdom, F. A. A., & Prins, N. (2010). *Psychophysics: A Practical Introduction*. London: Elsevier.

Kirby, A. V., Dickie, V. A., & Baranek, G. T. (2014). Sensory experiences of children with autism spectrum disorder: in their own words. *Autism*. doi: 10.1177/1362361314520756.

Kleiner, M., Brainard, D. H., & Pelli, D. G. (2007). What's new in Psychtoolbox-3? *Perception, 36 (ECVP Abstract Supplement)*, 14.

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

Kogan, C. S., Bertone, A., Cornish, K., Boutet, I., Der Kaloustian, V. M., Andermann, E., . . . Chaudhuri, A. (2004). Integrative cortical dysfunction and pervasive motion perception deficit in fragile X syndrome. *Neurology, 63*, 1634–1639.

Kogan, C. S., & Chaudhuri, A. (2005). Current dilemmas in the choice of stimulus regimes for the study of visual perceptual deficits in clinical populations. *Cahiers de Psychologie Cognitive (Current Psychology of Cognition), 23*(1-2), 132-142.

Koldewyn, K., Weigelt, S., Kanwisher, N., & Jiang, Y. (2013). Multiple object tracking in autism spectrum disorders. *Journal of Autism and Developmental Disorders, 43*(6), 1394-1405.

Koldewyn, K., Whitney, D., & Rivera, S. M. (2010). The psychophysics of visual motion and global form processing in autism. *Brain, 133*(2), 599-610.

Koldewyn, K., Whitney, D., & Rivera, S. M. (2011). Neural correlates of coherent and biological motion perception in autism. *Developmental Science, 14*(5), 1075-1088.

Kourtzi, Z., Augath, M., Logothetis, N. K., Movshon, J. A., & Kiorpes, L. (2006). Development of visually evoked cortical activity in infant macaque monkeys studied longitudinally with fMRI. *Magnetic Resonance Imaging, 24*(4), 359-366.

Kramer, J. H., Ellenberg, L., Leonard, J., & Share, L. J. (1996). Developmental sex differences in global-local perceptual bias. *Neuropsychology, 10*(3), 402.

Kravitz, D. J., Saleem, K. S., Baker, C. I., & Mishkin, M. (2011). A new neural framework for visuospatial processing. *Nature Reviews Neuroscience, 12*(4), 217-230.

Kröger, A., Bletsch, A., Krick, C., Siniatchkin, M., Jarczok, T. A., Freitag, C. M., & Bender, S. (2014). Visual event-related potentials to biological motion stimuli in autism spectrum disorders. *Social Cognitive and Affective Neuroscience, 9*(8), 1214-1222.

Lagae, L., Maes, H., Raiguel, S., Xiao, D. K., & Orban, G. A. (1994). Responses of macaque STS neurons to optic flow components: a comparison of areas MT and MST. *Journal of Neurophysiology, 71*(5), 1597-1626.

Lamme, V. A. F., Super, H., & Spekreijse, H. (1998). Feedforward, horizontal, and feedback processing in the visual cortex. *Current Opinion in Neurobiology, 8*(4), 529-535.

Lane, A. E., Molloy, C. A., & Bishop, S. L. (2014). Classification of children with autism spectrum disorder by sensory subtype: a case for sensory-based phenotypes. *Autism Research, 7*(3), 322-333.

Lane, A. E., Young, R. L., Baker, A. E. Z., & Angley, M. T. (2010). Sensory processing subtypes in autism: association with adaptive behavior. *Journal of Autism and Developmental Disorders, 40*, 112-122.

Lee, A. L. F., & Lu, H. (2010). A comparison of global motion perception using a multiple-aperture stimulus. *Journal of Vision, 10*(4), 1-16.

Leekam, S., Nieto, C., Libby, S., Wing, L., & Gould, J. (2007). Describing the sensory abnormalities of children and adults with autism. *Journal of Autism and Developmental Disorders, 37*(5), 894-910.

Liss, M., Saulnier, C., Fein, D., & Kinsbourne, M. (2006). Sensory and attention abnormalities in autistic spectrum disorders. *Autism, 10*(2), 155-172.

Liu, J., & Newsome, W. T. (2003). Functional organization of speed tuned neurons in visual area MT. *Journal of Neurophysiology, 89*, 246-256.

Liu, J., & Newsome, W. T. (2005). Correlation between speed perception and neural activity in the middle temporal visual area. *Journal of Neuroscience, 25*(3), 711-722.

Liu, T. (2013). Sensory processing and motor skill performance in elementary school children with autism spectrum disorder. *Perceptual Motor Skills, 116*(1), 197-209.

Lord, C., Petkova, E., Hus, V., Gan, W., Lu, F., Martin, D. M., . . . Gerdts, J. (2012). A multisite study of the clinical diagnosis of different autism spectrum disorders. *Archives of General Psychiatry, 69*(3), 306-313.

Lord, C., Risi, S., DiLavore, P. S., Shulman, C., Thurm, A., & Pickles, A. (2006). Autism from 2 to 9 years of age. *Archives of General Psychiatry, 63*(6), 694-701.

Lord, C., Rutter, M., DiLavore, P., Risi, S., Gotham, K., & Bishop, S. L. (2012). *Autism Diagnostic Observation Schedule (2nd ed., ADOS-2)*. Torrance, CA: Western Psychological Services.

Lord, C., Rutter, M., DiLavore, P. C., & Risi, S. (1999). *Autism Diagnostic Observation Schedule (WPS ed.)*. Los Angeles, CA: Western Psychological Services.

Lorteije, J. A. M., Van Wezel, R. J. A., & Van Der Smagt, M. J. (2008). Disentangling neural structures for processing of high-and low-speed visual motion. *European Journal of Neuroscience, 27*(9), 2341-2353.

Lovaas, O. I., Schreibman, L., Koegel, R., & Rehm, R. (1971). Selective responding by autistic children to multiple sensory input. *Journal of Abnormal Psychology, 103*, 211-222.

Lu, Z.-L., & Dosher, B. A. (1998). External noise distinguishes attention mechanisms. *Vision Research, 38*(9), 1183-1198.

Lu, Z.-L., & Sperling, G. (1995). The functional architecture of human visual motion perception. *Vision Research, 35*(19), 2697-2722.

Lu, Z.-L., & Sperling, G. (1996). Three systems for visual motion perception. *Current Directions in Psychological Science, 5*(2), 44-53.

Lu, Z.-L., & Sperling, G. (2001). Three-systems theory of human visual motion perception: review and update. *Journal of the Optical Society of America A, 18*(9), 2331-2370.

Macmillan, N. A., & Creelman, C. D. (1991). *Detection theory: A user's guide*. Cambridge: Cambridge University Press.

Mandell, D. (2011). The heterogeneity in clinical presentation among individuals on the autism spectrum is a remarkably puzzling facet of this set of disorders. *Autism, 15*(3), 259-261.

Mandell, D., & Lecavalier, L. (2014). Should we believe the Centers for Disease Control and Prevention’s autism spectrum disorder prevalence estimates? *Autism, 18*(5), 482-484.

Mandy, W., Chilvers, R., Chowdhury, U., Salter, G., Seigal, A., & Skuse, D. (2012). Sex differences in autism spectrum disorder: evidence from a large sample of children and adolescents. *Journal of Autism and Developmental Disorders, 42*(7), 1304-1313.

Mandy, W. P. L., Charman, T., & Skuse, D. H. (2012). Testing the construct validity of proposed criteria for DSM-5 autism spectrum disorder. *Journal of the American Academy of Child and Adolescent Psychiatry, 51*(1), 41–50.

Manning, C., Aagten-Murphy, D., & Pellicano, E. (2012). The development of speed discrimination abilities. *Vision Research, 70*, 27-33.

Manning, J. T., Scutt, D., Wilson, J., & Lewis-Jones, D. I. (1998). The ratio of 2nd to 4th digit length: a predictor of sperm numbers and concentrations of testosterone, luteinizing hormone and oestrogen. *Human Reproduction, 13*(11), 3000-3004.

Mannion, A., & Leader, G. (2013). Comorbidity in autism spectrum disorder: a literature review. *Research in Autism Spectrum Disorders, 7*(12), 1595-1616.

Mareschal, D., Harris, P., & Plunkett, K. (1997). Effects of linear and angular velocity on 2-, 4-, and 6-month-olds' visual pursuit behaviors. *Infant Behavior and Development, 20*(4), 435-448.

Matson, J. L., Rieske, R. D., & Williams, L. W. (2013). The relationship between autism spectrum disorders and attention-deficit/hyperactivity disorder: an overview. *Research in Developmental Disabilities, 34*(9), 2475-2484.

Matthews, N., Luber, B., Qian, N., & Lisanby, S. (2001). Transcranial magnetic stimulation differentially affects speed and direction judgments. *Experimental Brain Research, 140*(4), 397-406.

Maximo, J., Cadena, E., & Kana, R. (2014). The implications of brain connectivity in the neuropsychology of autism. *Neuropsychology Review, 24,* 16-31.

McDonnell, M. D., & Abbott, D. (2009). What is stochastic resonance? Definitions, misconceptions, debates, and its relevance to biology. *PLoS Computational Biology, 5*(5), e1000348.

McDonnell, M. D., & Ward, L. M. (2011). The benefits of noise in neural systems: bridging theory and experiment. *Nature Reviews Neuroscience, 12*(7), 415-426.]

McIntosh, A. R., Kovacevic, N., & Itier, R. J. (2008). Increased brain signal variability accompanies lower behavioral variability in development. *PLoS Computational Biology, 4*(7), e1000106.

McKay, L., Mackie, J., Piggott, J., Simmons, D. R., & Pollick, F. E. (2006). Biological motion processing in autistic spectrum conditions: perceptual and social factors. *Journal of Vision, 6*(6), 1036.

McKay, L. S., Simmons, D. R., McAleer, P., Marjoram, D., Piggot, J., & Pollick, F. E. (2012). Do distinct atypical cortical networks process biological motion information in adults with Autism Spectrum Disorders? *NeuroImage, 59*(2), 1524-1533.

Meese, T. S., Harris, M. G., & Ca Freeman, T. (1995). Speed gradients and the perception of surface slant: analysis is two-dimensional not one-dimensional. *Vision Research, 35*(20), 2879-2888.

Meier, K., & Giaschi, D. (2014). The maturation of global motion perception depends on the spatial and temporal offsets of the stimulus. *Vision Research, 95,* 61-67.

Mestre, D., Rondan, C., Masson, G., Castet, E., Deruelle, C., & Gepner, B. (2002). Evaluation de la vision du mouvement chez des enfants autistes au moyen du nystagmus opto-cinétique. *Revue TIPA, 21*, 192-198.

Mikami, A., Newsome, W. T., & Wurtz, R. H. (1986). Motion selectivity in macaque visual cortex. II. Spatiotemporal range of directional interactions in MT and V1. *Journal of Neurophysiology, 55*(6), 1328-1339.

Miller, L. J., Anzalone, M. E., Lane, S. J., Cermak, S. A., & Osten, E. T. (2007). Concept evolution in sensory integration: a proposed nosology for diagnosis. *American Journal of Occupational Therapy, 61*(2), 135-140.

Milne, E. (2011). Increased intra-participant variability in children with autistic spectrum disorders: evidence from single-trial analysis of evoked EEG. *Frontiers in Psychology, 2*(51), 1-12.

Milne, E., Swettenham, J., Hansen, P., Campbell, R., Jeffries, H., & Plaisted, K. (2002). High motion coherence thresholds in children with autism. *Journal of Child Psychology and Psychiatry, 43*(2), 255-263.

Milne, E., & Szczerbinski, M. (2009). Global and local perceptual style, field-independence, and central coherence: an attempt at concept validation. *Advances in Cognitive Psychology, 5*(1), 1-26.

Milne, E., White, S., Campbell, R., Swettenham, J., Hansen, P., & Ramus, F. (2006). Motion and form coherence detection in autistic spectrum disorder: relationship to motor control and 2:4 digit ratio. *Journal of Autism and Developmental Disorders, 36*(2), 225-237.

Milner, A. D., & Goodale, M. A. (1995). *The Visual Brain in Action.* Oxford: Oxford University Press.

Minshew, N. J., Goldstein, G., & Siegel, D. J. (1997). Neuropsychologic functioning in autism: profile of a complex information processing disorder. *Journal of the International Neuropsychological Society, 3*(4), 303-316.

Minshew, N. J., & Williams, D. L. (2007). The new neurobiology of autism: cortex, connectivity, and neuronal organization. *Archives of Neurology, 64*(7), 945-950.

Mishkin, M., Ungerleider, L., & Macko, K. A. (1983). Object vision and spatial vision: two critical pathways. *Trends in Neurosciences, 6*, 414-417.

Mitchell, P., Mottron, L., Soulières, I., & Ropar, D. (2010). Susceptibility to the Shepard illusion in participants with autism: reduced top-down influences within perception? *Autism Research, 3*, 113-119.

Möhring, W., Libertus, M. E., & Bertin, E. (2012). Speed discrimination in 6- and 10-month-old infants follows Weber's law. *Journal of Experimental Child Psychology, 111*, 405-418.

Molloy, C., Dietrich, K., & Bhattacharya, A. (2003). Postural stability in children with autism spectrum disorder. *Journal of Autism and Developmental Disorders, 33*(6), 643-652.

Moore, D. G., Hobson, R. P., & Lee, A. (1997). Components of person perception: an investigation with autistic, non-autistic retarded and typically developing children and adolescents. *British Journal of Developmental Psychology, 15*(4), 401-423.

Morrone, M. C. (2014). Development and plasticity of human cortical network for motion analysis. *Perception, 43 (ECVP Abstract Supplement)*, 61.

Mottron, L., Bouvet, L., Bonnel, A., Samson, F., Burack, J. A., Dawson, M., & Heaton, P. (2013). Veridical mapping in the development of exceptional autistic abilities. *Neuroscience and Biobehavioral Reviews, 37*(2), 209-228.

Mottron, L., & Burack, J. A., (2001). Enhanced perceptual functioning in the development of autism. In J. A. Burack, T. Charman, N. Yirmiya, & P. R. Zelazo (Eds.), *The Development of Autism: Perspectives from Theory and Research*. Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers.

Mottron, L., Burack, J. A., Iarocci, G., Belleville, S., & Enns, J. T. (2003). Locally oriented perception with intact global processing among adolescents with high-functioning autism: evidence from multiple paradigms. *Journal of Child Psychology and Psychiatry, 44*(6), 904-913.

Mottron, L., Dawson, M., Soulières, I., Hubert, B., & Burack, J. (2006). Enhanced perceptual functioning in autism: an update, and eight principles of autistic perception. *Journal of Autism and Developmental Disorders, 36*(1), 27-43.

Movshon, J. A., Rust, N. C., Kohn, A., Kiorpes, L., & Hawken, M. J. (2004). Receptive-field properties of MT neurons in infant macaques. *Perception, 33*, 27.

Murphy, P., Brady, N., Fitzgerald, M., & Troje, N. F. (2009). No evidence for impaired perception of biological motion in adults with autistic spectrum disorders. *Neuropsychologia, 47*(14), 3225-3235.

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.

Narasimhan, S., & Giaschi, D. (2012). The effect of dot speed and density on the development of global motion perception. *Vision Research, 62*, 102-107.

Nardini, M., Bedford, R., & Mareschal, D. (2010). Fusion of visual cues is not mandatory in children. *Proceedings of the National Academy of Sciences, 107*(39), 17041-17046.

Nardini, M., Jones, P., Bedford, R., & Braddick, O. (2008). Development of cue integration in human navigation. *Current Biology, 18*(9), 689-693.

Nassi, J. J., & Callaway, E. M. (2009). Parallel processing strategies of the primate visual system. *Nature Reviews Neuroscience, 10*(5), 360-372.

National Institute for Health and Care Excellence (2011). Autism: recognition, referral and diagnosis of children and young people on the autism spectrum. Clinical guidelines, CG128. Retrieved from http://www.nice.org.uk/guidance/Cg128.

Nealey, T. A., & Maunsell, J. H. (1994). Magnocellular and parvocellular contributions to the responses of neurons in macaque striate cortex. *Journal of Neuroscience, 14*(4), 2069-2079.

Neveu, M. M., Jeffery, G., Moore, A. T., & Dakin, S. C. (2009). Deficits in local and global motion perception arising from abnormal eye movements. *Journal of Vision, 9*(4:9), 1-15.

O'Connor, E., Margrain, T. H., & Freeman, T. C. A. (2010). Age, eye movement and motion discrimination. *Vision Research, 50*, 2588-2599.

O'Hearn, K., Franconeri, S., Wright, C., Minshew, N., & Luna, B. (2013). The development of individuation in autism. *Journal of Experimental Psychology: Human Perception and Performance, 39*(2), 494-509.

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

O'Riordan, M. A., Plaisted, K. C., Driver, J., & Baron-Cohen, S. (2001). Superior visual search in autism. *Journal of Experimental Psychology: Human Perception & Performance, 27*(3), 719-730.

Orban, G. A., Saunders, R. C., & Vandenbussche, E. (1995). Lesions of the Superior Temporal cortical motion areas impair speed discrimination in the macaque monkey. *European Journal of Neuroscience, 7*, 2261-2276.

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.

Palomares, M., & Shannon, M. T. (2013). Global dot integration in typically developing children and in Williams Syndrome. *Brain and Cognition, 83*(3), 262-270.

Pardhan, S. (2004). Contrast sensitivity loss with aging: sampling efficiency and equivalent noise at different spatial frequencies. *Journal of the Optical Society of America A, 21*(2), 169-175.

Pardhan, S., Gilchrist, J., Elliott, D. B., & Beh, G. K. (1996). A comparison of sampling efficiency and internal noise level in young and old subjects. *Vision Research, 36*(11), 1641-1648.

Parrish, E. E., Giaschi, D. E., Boden, C., & Dougherty, R. (2005). The maturation of form and motion perception in school age children. *Vision Research, 45*(7), 827-837.

Parron, C., Da Fonseca, D., Santos, A., Moore, D., Monfardini, E., & Deruelle, C. (2008). Recognition of biological motion in children with autistic spectrum disorders. *Autism, 12*(3), 261-274.

Pavlova, M. A. (2012). Biological motion processing as a hallmark of social cognition. *Cerebral Cortex, 22*(5), 981-995.

Pelli, D. G. (1990). The quantum efficiency of vision. In C. Blakemore (Ed.), *Vision: Coding and Efficiency*. Cambridge, UK: Cambridge University Press.

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: transforming numbers into movies. *Spatial Vision, 10,* 437-442.

Pellicano, E. (2013). Sensory symptoms in autism: a blooming, buzzing confusion? *Child Development Perspectives, 7*(3), 143-148.

Pellicano, E., & Burr, D. (2012). When the world becomes ‘too real’: a Bayesian explanation of autistic perception. *Trends in Cognitive Sciences, 16*(10), 504-510.

Pellicano, E., Gibson, L., Maybery, M., Durkin, K., & Badcock, D. R. (2005). Abnormal global processing along the dorsal visual pathway in autism: a possible mechanism for weak visuospatial coherence? *Neuropsychologia, 43*(7), 1044-1053.

Pellicano, E., & Gibson, L. Y. (2008). Investigating the functional integrity of the dorsal visual pathway in autism and dyslexia. *Neuropsychologia, 46*, 2593-2596.

Perrone, J. A. (2005). Economy of scale: a motion sensor with variable speed tuning. *Journal of Vision, 5*(1), 28-33.

Perrone, J. A., & Thiele, A. (2002). A model of speed tuning in MT neurons. *Vision Research, 42,* 1035-1051.

Pfeiffer, B., Kinnealey, M., Reed, C., & Herzberg, G. (2005). Sensory modulation and affective disorders in children and adolescents with Asperger's disorder. *American Journal of Occupational Therapy, 59*(3), 335-345.

Pilly, P. K., & Seitz, A. R. (2009). What a difference a parameter makes: a psychophysical comparison of random dot motion algorithms. *Vision Research, 49*(13), 1599-1612.

Plaisted, K., Dobler, V., Bell, S., & Davis, G. (2006). The microgenesis of global perception in autism. *Journal of Autism and Developmental Disorders, 36*(1), 107-116.

Plaisted, K., O'Riordan, M., & Baron-Cohen, S. (1998a). 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.

Plaisted, K., O'Riordan, M., & Baron-Cohen, S. (1998b). Enhanced visual search for a conjunctive target in autism: a research note. *Journal of Child Psychology and Psychiatry, 39*(5), 777-783.

Plaisted, K., Saksida, L., Alcántara, J., & Weisblatt, E. (2003). Towards an understanding of the mechanisms of weak central coherence effects: experiments in visual configural learning and auditory perception. *Philosophical*

Transactions of the Royal Society of London. Series B: Biological Sciences, 358(1430), 375-386.

Plaisted, K., Swettenham, J., & Rees, L. (1999). Children with autism show local precedence in a divided attention task and global precedence in a selective attention task. *Journal of Child Psychology and Psychiatry, 40*(5), 733-742.

Plaisted, K. C. (2000). Aspects of autism that theory of mind cannot explain. In S. Baron-Cohen, H. Tager-Flusberg & D. J. Cohen (Eds.), *Understanding Other Minds: Perspectives From Developmental Cognitive Neuroscience (2nd ed.)*. Oxford, UK: Oxford University Press.

Plaisted, K. C. (2001). Reduced generalization in autism: an alternative to weak central coherence. In J. A. Burack, T. Charman, N. Yirmiya & P. D. Zelazo (Eds.), *The Development of Autism: Perspectives From Theory and Research*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Price, K. J., Shiffrar, M., & Kerns, K. A. (2012). Movement perception and movement production in Asperger's syndrome. *Research in Autism Spectrum Disorders, 6*(1), 391-398.

Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., & Frith, U. (2003). Theories of developmental dyslexia: insights from a multiple case study of dyslexic adults. *Brain, 126*(4), 841-865.

Rasche, C., & Gegenfurtner, K. R. (2009). Precision of speed discrimination and smooth pursuit eye movements. *Vision Research, 49*(5), 514-523.

Raudies, F., & Neumann, H. (2010). A neural model of the temporal dynamics of figure–ground segregation in motion perception. *Neural Networks, 23*(2), 160-176.

Remington, A., Cartwright-Finch, U., & Lavie, N. (2014). I can see clearly now: the effects of age and perceptual load on inattentional blindness. *Frontiers in Human Neuroscience, 8*(229), 1-11.

Remington, A., Swettenham, J., Campbell, R., & Coleman, M. (2009). Selective attention and perceptual load in autism spectrum disorder. *Psychological Science, 20*(11), 1388-1393.

Remington, A. M., Swettenham, J. G., & Lavie, N. (2012). Lightening the load: perceptual load impairs visual detection in typical adults but not in autism. *Journal of Abnormal Psychology, 121*(2), 544-551.

Rivet, T. T., & Matson, J. L. (2011). Review of gender differences in core symptomatology in autism spectrum disorders. *Research in Autism Spectrum Disorders, 5*(3), 957-976.

Roach, N. W., & Hogben, J. H. (2007). Impaired filtering of behaviourally irrelevant visual information in dyslexia. *Brain, 130*(3), 771-785.

Robertson, A. E. (2012). *Sensory Experiences of Individuals with Autism Spectrum Disorder and Autistic Traits: A Mixed Methods Approach* (PhD thesis). University of Glasgow. Retrieved from http://theses.gla.ac.uk/3769/.

Robertson, A. E., & Simmons, D. R. (2013). The relationship between sensory sensitivity and autistic traits in the general population. *Journal of Autism and Developmental Disorders, 43*(4), 775-784.

Robertson, C. E., Kravitz, D. J., Freyberg, J., Baron-Cohen, S., & Baker, C. I. (2013). Slower rate of binocular rivalry in autism. *Journal of Neuroscience, 33*(43), 16983-16991.

Robertson, C. E., Martin, A., Baker, C. I., & Baron-Cohen, S. (2012). Atypical integration of motion signals in autism spectrum conditions. *PLoS One, 7*(11), 1-9.

Robertson, C. E., Thomas, C., Kravitz, D. J., Wallace, G. L., Baron-Cohen, S., Martin, A., & Baker, C. I. (2014). Global motion perception deficits in autism are reflected as early as primary visual cortex. *Brain*, *137*(9), 2588-2599.

Robinson, E. B., Koenen, K. C., McCormick, M. C., Munir, K., Hallett, V., . . . Ronald, A. (2011). Evidence that autistic traits show the same etiology in the general population and at the quantitative extremes (5%, 2.5%, and 1%). *Archives of General Psychiatry, 68*(11), 1113-1121.

Rogers, S. J., Hepburn, S., & Wehner, E. (2003). Parent reports of sensory symptoms in toddlers with autism and those with other developmental disorders. *Journal of Autism and Developmental Disorders, 33*(6), 631-642.

Rogers, S. J., & Ozonoff, S. (2005). What do we know about sensory dysfunction in autism? A critical review of the empirical evidence. *Journal of Child Psychology and Psychiatry, 46*(12), 1255-1268.

Ronconi, L., Gori, S., Ruffino, M., Franceschini, S., Urbani, B., Molteni, M., & Facoetti, A. (2012). Decreased coherent motion discrimination in autism spectrum disorder: the role of attentional zoom-out deficit. *PLos One, 7*(11), 1-9.

Ronemus, M., Iossifov, I., Levy, D., & Wigler, M. (2014). The role of de novo mutations in the genetics of autism spectrum disorders. *Nature Reviews Genetics, 15*(2), 133-141.

Ropar, D., & Mitchell, P. (2002). Shape constancy in autism: the role of prior knowledge and perspective cues. *Journal of Child Psychology and Psychiatry, 43*(5), 647-653.

Rubenstein, J. L. R., & Merzenich, M. M. (2003). Model of autism: increased ratio of excitation/inhibition in key neural systems. *Genes, Brain and Behavior, 2*(5), 255-267.

Rutherford, M. D., & Troje, N. (2012). IQ predicts biological motion perception in autism spectrum disorders. *Journal of Autism and Developmental Disorders, 42*(4), 557-565.

Rutter, M., Bailey, A., & Lord, C. (2003). *Social Communication Questionnaire*. Los Angeles, CA: Western Psychological Services.

Samson, F., Mottron, L., Soulières, I., & Zeffiro, T. A. (2012). Enhanced visual functioning in autism: an ALE meta-analysis. *Human Brain Mapping, 33*(7), 1553-1581.

Sanchez-Marin, F., & Padilla-Medina, J. (2008). A psychophysical test of the visual pathway of children with autism. *Journal of Autism and Developmental Disorders, 38*(7), 1270-1277.

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), 1-7.

Schaaf, R. C., Toth-Cohen, S., Johnson, S. L., Outten, G., & Benevides, T. W. (2011). The everyday routines of families of children with autism: examining the impact of sensory processing difficulties on the family. *Autism, 15*(3), 373-389.

Schall, C., Wehman, P., & McDonough, J. L. (2012). Transition from school to work for students with autism spectrum disorders: understanding the process and achieving better outcomes. *Pediatric Clinics of North America, 59*(1), 189-202.

Schwarzkopf, D. S., Anderson, E. J., de Haas, B., White, S. J., & Rees, G. (2014). Larger extrastriate population receptive fields in autism spectrum disorders. *Journal of Neuroscience, 34*(7), 2713-2724.

Shah, A., & Frith, U. (1983). An islet of ability in autistic children: a research note. *Journal of Child Psychology and Psychiatry, 24*, 613-620.

Shah, A., & Frith, U. (1993). Why do autistic individuals show superior performance on the block design task? *Journal of Child Psychology and Psychiatry, 34*(8), 1351-1364.

Shukla, D. K., Keehn, B., & Müller, R.-A. (2011). Tract-specific analyses of diffusion tensor imaging show widespread white matter compromise in autism spectrum disorder. *Journal of Child Psychology and Psychiatry, 52*(3), 286-295.

Sillito, A. M., Cudeiro, J., & Jones, H. E. (2006). Always returning: feedback and sensory processing in visual cortex and thalamus. *Trends in Neurosciences, 29*(6), 307-316.

Simmons, D. R., Robertson, A. E., McKay, L. S., Toal, E., McAleer, P., & Pollick, F. E. (2009). Vision in autism spectrum disorders. *Vision Research, 49*(22), 2705-2739.

Simonoff, E., Pickles, A., Charman, T., Chandler, S., Loucas, T., & Baird, G. (2008). Psychiatric disorders in children with autism spectrum disorders: prevalence, comorbidity, and associated factors in a population-derived sample. *Journal of the American Academy of Child and Adolescent Psychiatry, 47*(8), 921-929.

Sinclair, J. (2013). Why I dislike “person first” language. *Autonomy, 1*(2).

Skewes, J. C., Jegindø, E.-M., & Gebauer, L. (2014). Perceptual inference and autistic traits. *Autism*, doi:10.1177/1362361313519872.

Skoczenski, A. M., & Norcia, A. M. (1998). Neural noise limitations on infant visual sensitivity. *Nature, 391*(6668), 697-700.

Spencer, J., O'Brien, J., Riggs, K., Braddick, O., Atkinson, J., & Wattam-Bell, J. (2000). Motion processing in autism: evidence for a dorsal stream deficiency. *NeuroReport, 11*(12), 2765-2767.

Spencer, J., & O'Brien, J. M. D. (2006). Visual form-processing deficits in autism. *Perception, 35*(8), 1047-1055.

Sperling, A. J., Lu, Z.-L., Manis, F. R., & Seidenberg, M. S. (2005). Deficits in perceptual noise exclusion in developmental dyslexia. *Nature Neuroscience, 8*(7), 862-863.

Sperling, A. J., Lu, Z.-L., Manis, F. R., & Seidenberg, M. S. (2006). Motion-perception deficits and reading impairment: it's the noise, not the motion. *Psychological Science, 17*(12), 1047-1053.

Stanfield, A. C., McIntosh, A. M., Spencer, M. D., Philip, R., Gaur, S., & Lawrie, S. M. (2008). Towards a neuroanatomy of autism: a systematic review and meta-analysis of structural magnetic resonance imaging studies. *European Psychiatry, 23*(4), 289-299.

Stevens, J. P. (1992). *Applied Multivariate Statistics for the Social Sciences (2nd ed.)*. Hillsdale, NJ: Erlbaum.

Stevens, S. S. (1957). On the psychophysical law. *Psychological Review, 64*(3), 153-181.

Stevenson, R. A., Siemann, J. K., Schneider, B. C., Eberly, H. E., Woynaroski, T. G., Camarata, S. M., & Wallace, M. T. (2014). Multisensory temporal integration in autism spectrum disorders. *Journal of Neuroscience, 34*(3), 691-697.

Stone, W. L., Lee, E. B., Ashford, L., Brissie, J., Hepburn, S. L., Coonrod, E. E., & Weiss, B. H. (1999). Can autism be diagnosed accurately in children under 3 years? *Journal of Child Psychology and Psychiatry, 40*(2), 219-226.

Sunaert, S., Van Hecke, P., Marchal, G., & Orban, G. A. (1999). Motion-responsive regions of the human brain. *Experimental Brain Research, 127*(4), 355-370.

Sunaert, S., Van Hecke, P., Marchal, G., & Orban, G. A. (2000). Attention to speed of motion, speed discrimination, and task difficulty: an fMRI study. *NeuroImage, 11*, 612-623.

Swettenham, J., Remington, A., Laing, K., Fletcher, R., Coleman, M., & Gomez, J.-C. (2013). Perception of pointing from biological motion point-light displays in typically developing children and children with autism spectrum disorder. *Journal of Autism and Developmental Disorders, 43*(6), 1437-1446.

Tabachnick, B. G., & Fidell, L. S. (2007). *Using Multivariate Statistics (5th ed.)*. Boston, MA: Allyn and Bacon.

Takarae, Y., Luna, B., Minshew, N. J., & Sweeney, J. A. (2008). Patterns of visual sensory and sensorimotor abnormalities in autism vary in relation to history of early language delay. *Journal of the International Neuropsychological Society, 14*(6), 980-989.

Takarae, Y., Luna, B., Minshew, N. J., & Sweeney, J. A. (2014). Visual motion processing and visual sensorimotor control in autism. *Journal of the International Neuropsychological Society, 20*(01), 113-122.

Talay-Ongan, A., & Wood, K. (2000). Unusual sensory sensitivities in autism: a possible crossroads. *International Journal of Disability, Development and Education, 47*(2), 201-212.

Tanaka, K., Hikosaka, K., Saito, H., Yukie, M., Fukada, Y., & Iwai, E. (1986). Analysis of local and wide-field movements in the superior temporal visual areas of the macaque monkey. *Journal of Neuroscience, 6*(1), 134-144.

Tardif, C., Lainé, F., Rodriguez, M., & Gepner, B. (2007). Slowing down presentation of facial movements and vocal sounds enhances facial expression recognition and induces facial–vocal imitation in children with autism. *Journal of Autism and Developmental Disorders, 37*(8), 1469-1484.

Tardif, C., Thomas, K., Gepner, B., & Rey, V. (2002). Contribution a l'evaluation du systeme phonologique explicite chez des enfants autistes. *Revue Parole*, 35-72.

Tavassoli, T., Miller, L. J., Schoen, S. A., Nielsen, D. M., & Baron-Cohen, S. (2014). Sensory over-responsivity in adults with autism spectrum conditions. *Autism, 18*(4), 428-432.

Taylor, J., & Seltzer, M. (2010). Changes in the autism behavioral phenotype during the transition to adulthood. *Journal of Autism and Developmental Disorders, 40*(12), 1431-1446.

Thomas, M. S. C., Annaz, D., Ansari, D., Scerif, G., Jarrold, C., & Karmiloff-Smith, A. (2009). Using developmental trajectories to understand developmental disorders. *Journal of Speech, Language and Hearing Research, 52*(2), 336-358.

Thompson, P., Brooks, K., & Hammett, S. T. (2006). Speed can go up as well as down at low contrast: implications for models of motion perception. *Vision Research, 46*, 782-786.

Tibber, M. S., Kelly, M. G., Jansari, A., Dakin, S. C., & Shepherd, A. J. (2014). An inability to exclude visual noise in migraine. *Investigative Ophthalmology and Visual Science, 55*(4), 2539-2546.

Tootell, R. B. H., Reppas, J. B., Kwong, K. K., Malach, R., Born, R. T., Brady, T. J., . . . Belliveau, J. W. (1995). Functional analysis of human MT and related visual cortical areas using magnetic resonance imaging. *Journal of Neuroscience, 15*(4), 3215.

Treutwein, B. (1995). Adaptive psychophysical procedures. *Vision Research, 35*(17), 2503-2522.

Tsermentseli, S., O’Brien, J., & Spencer, J. (2008). Comparison of form and motion coherence processing in autistic spectrum disorders and dyslexia. *Journal of Autism and Developmental Disorders, 38*(7), 1201-1210.

Uddin, L. Q., Supekar, K., & Menon, V. (2013). Reconceptualizing functional brain connectivity in autism from a developmental perspective. *Frontiers in Human Neuroscience, 7*(458), 1-11.

Vakorin, V. A., Lippe, S., & McIntosh, A. R. (2011). Variability of brain signals processed locally transforms into higher connectivity with brain development. *Journal of Neuroscience, 31*(17), 6405-6413.

Van de Cruys, S., de-Wit, L., Evers, K., Boets, B., & Wagemans, J. (2013). Weak priors versus overfitting of predictions in autism: reply to Pellicano and Burr (TICS, 2012). *i-Perception, 4*(2), 95.

Van de Cruys, S., Evers, K., Van der Hallen, R., Van Eylen, L., Boets, B., de-Wit, L., & Wagemans, J. (in press). Precise minds in uncertain worlds: predictive coding in autism. *Psychological Review.*

Van der Smagt, M. J., Verstraten, F., A J, & Paffen, C. L. E. (2010). Center-surround effects on perceived speed. *Vision Research, 50*, 1900-1904.

Vandenbroucke, M. W. G., Scholte, H. S., Engeland, H., Lamme, V. A. F., & Kemner, C. (2008). Coherent versus component motion perception in autism spectrum disorder. *Journal of Autism and Developmental Disorders, 38*(5), 941-949.

Velázquez, J. L. P., & Galán, R. F. (2013). Information gain in the brain's resting state: a new perspective on autism. *Frontiers in Neuroinformatics, 7*(37), 1-10.

Verghese, P., & McKee, S. P. (2006). Motion grouping impairs speed discrimination. *Vision Research, 46*, 1540-1546.

Verstraten, F. A. J., Cavanagh, P., & Labianca, A. T. (2000). Limits of attentive tracking reveal temporal properties of attention. *Vision Research, 40*(26), 3651-3664.

Vissers, M. E., Cohen, M. X., & Geurts, H. M. (2012). Brain connectivity and high functioning autism: a promising path of research that needs refined models, methodological convergence, and stronger behavioral links. *Neuroscience and Biobehavioral Reviews, 36*(1), 604-625.

Volkmann, F. C., & Dobson, M. V. (1976). Infant responses of ocular fixation to moving visual stimuli. *Journal of Experimental Child Psychology, 22*, 86-99.

Volkmar, F., Siegel, M., Woodbury-Smith, M., King, B., McCracken, J., & State, M. (2014). Practice parameter for the assessment and treatment of children and adolescents with autism spectrum disorder. *Journal of the American Academy of Child and Adolescent Psychiatry, 53*(2), 237-257.

Volkmar, F. R., & Klin, A. (2005). Issues in the classification of autism and related conditions. In F. R. Volkmar, R. Paul, A. Klin & D. Cohen (Eds.), *Handbook of Autism and Pervasive Developmental Disorders, Vol. 1 (3rd ed.).* Hoboken, NJ: John Wiley & Sons, Inc.

Wagemans, J., Van der Hallen, R., Chamberlain, R., Van de Cruys, S., & de-Wit, L. (2014). (in)Validating measures of local and global processing. *Perception, 43 (ECVP Abstract Supplement),* 175.

Wagner, D., Manahilov, V., Loffler, G., Gordon, G. E., & Dutton, G. N. (2010). Visual noise selectively degrades vision in migraine. *Investigative Ophthalmology and Visual Science, 51*(4), 2294-2299.

Wang, L., Mottron, L., Peng, D., Berthiaume, C., & Dawson, M. (2007). Local bias and local-to-global interference without global deficit: a robust finding in autism under various conditions of attention, exposure time, and visual angle. *Cognitive Neuropsychology, 24*(5), 550-574.

Wang, Y., Fujita, I., Tamura, H., & Murayama, Y. (2002). Contribution of GABAergic inhibition to receptive field structures of monkey inferior temporal neurons. *Cerebral Cortex, 12*(1), 62-74.

Warren Jr, W. H., & Saunders, J. A. (1995). Perceiving heading in the presence of moving objects. *Perception*, *24*(1), 315-332.

Warren, W. H., & Hannon, D. J. (1988). Direction of self-motion is perceived from optical flow. *Nature, 336*(6195), 162-163.

Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nature Neuroscience, 4*(2), 213-216.

Watamaniuk, S. N., Flinn, J., & Stohr, R. E. (2003). Segregation from direction differences in dynamic random-dot stimuli. *Vision Research, 43*, 171-180.

Waterhouse, L. (2013). *Rethinking Autism: Variation and Complexity*. Waltham, MA: Academic Press.

Watson, A. B. (1979). Probability summation over time. *Vision Research, 19*(5), 515-522.

Watson, A. B., & Pelli, D. G. (1983). QUEST: a Bayesian adaptive psychometric method. *Perception and Psychophysics, 33*(2), 113-120.

Wattam-Bell, J. (1991). The development of motion-specific cortical responses in infants. *Vision Research, 31*, 287.

Webster, K. E., Dickinson, J. E., Battista, J., McKendrick, A. M., & Badcock, D. R. (2011). Increased internal noise cannot account for motion coherence processing deficits in migraine. *Cephalalgia, 31*(11), 1199-1210.

Wechsler, D. (1999). *Wechsler Abbreviated Scale of Intelligence*. San Antonio, TX: Psychological Corporation.

Wechsler, D. (2011). *WASI-II: Wechsler Abbreviated Scale of Intelligence (2nd ed.)*. San Antonio, Texas: Psychological Corporation.

Weiss, Y., Simoncelli, E. P., & Adelson, E. H. (2002). Motion illusions as optimal percepts. *Nature Neuroscience, 5*(6), 598-604.

Werling, D. M., & Geschwind, D. H. (2013). Sex differences in autism spectrum disorders. *Current Opinion in Neurology, 26*(2), 146-153.

Whitehouse, A. J. O., Mattes, E., Maybery, M. T., Dissanayake, C., Sawyer, M., Jones, R. M., . . . Hickey, M. (2012). Perinatal testosterone exposure and autistic-like traits in the general population: a longitudinal pregnancy-cohort study. *Journal of Neurodevelopmental Disorders, 4*(25), 1-12.

Wiesenfeld, K., & Moss, F. (1995). Stochastic resonance and the benefits of noise: from ice ages to crayfish and SQUIDs. *Nature, 373*(6509), 33-36.

Wiggins, L. D., Robins, D. L., Bakeman, R., & Adamson, L. B. (2009). Sensory abnormalities as distinguishing symptoms of autism spectrum disorders in young children. *Journal of Autism and Developmental Disorders, 39*(7), 1087-1091.

Wightman, F., & Allen, P. (1992). Individual differences in auditory capability among preschool children. In L. A. Werner & E. W. Rubel (Eds.), *Developmental Psychoacoustics.* Washington, DC: American Psychological Association.

Wightman, F., Allen, P., Dolan, T., Kistler, D., & Jamieson, D. (1989). Temporal resolution in children. *Child Development, 60*, 611-624.

Wilcox, T., Hawkins, L. B., Hirskkowitz, A., & Boas, D. A. (2014). Cortical activation to object shape and speed of motion during the first year. *NeuroImage, 99,* 129-141.

Wilcox, T., & Schweinle, A. (2003). Infants' use of speed information to individuate objects in occlusion events. *Infant Behavior and Development, 26*(2), 253-282.

Williams, B. R., Hultsch, D. F., Strauss, E. H., Hunter, M. A., & Tannock, R. (2005). Inconsistency in reaction time across the life span. *Neuropsychology, 19*(1), 88-96.

Williams, D. (1999). *Nobody Nowhere: The Remarkable Autobiography of an Autistic Girl*. London: Jessica Kingsley.

Williams, K., Glasson, E. J., Wray, J., Tuck, M., Helmer, M., Bower, C. I., & Mellis, C. M. (2005). Incidence of autism spectrum disorders in children in two Australian states. *Medical Journal of Australia, 182*(3), 108-111.

Wilmer, J. B., Richardson, A. J., Chen, Y., & Stein, J. F. (2004). Two visual motion processing deficits in developmental dyslexia associated with different reading skills deficits. *Journal of Cognitive Neuroscience, 16*(4), 1-13.

Wilson, B. N., Kaplan, B. J., Crawford, S. G., & Roberts, G. (2007). Developmental Coordination Questionnaire 2007 (DCDQ'07). Retrieved from http://www.dcdq.ca.

Witwer, A. N., & Lecavalier, L. (2008). Examining the validity of autism spectrum disorder subtypes. *Journal of Autism and Developmental Disorders, 38*(9), 1611-1624.

World Health Organisation (1993). *The ICD-10 Classification of Mental and Behavioural Disorders. Diagnostic Criteria for Research.* Geneva: World Health Organisation.

Zachor, D., & Ben-Itzchak, E. (2014). The relationship between clinical presentation and unusual sensory interests in autism spectrum disorders: a preliminary investigation. *Journal of Autism and Developmental Disorders, 44*(1), 229-235.

Zilbovicius, M., Meresse, I., Chabane, N., Brunelle, F., Samson, Y., & Boddaert, N. (2006). Autism, the superior temporal sulcus and social perception. *Trends in Neurosciences, 29*(7), 359-366.