How do people with autism process multisensory information?

A thesis submitted to the University of Manchester for the degree of Doctor of Philosophy in the Faculty of Medical and Human Sciences

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<tr>
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<th>Description</th>
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<tbody>
<tr>
<td>2IFC</td>
<td>Two Interval Forced Choice</td>
</tr>
<tr>
<td>AASP</td>
<td>Adolescent and Adult Sensory Profile</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>AV</td>
<td>Auditory-Visual</td>
</tr>
<tr>
<td>ADOS</td>
<td>Autism Diagnostic Observation Schedule</td>
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<tr>
<td>ASC</td>
<td>Autism Spectrum Condition</td>
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<tr>
<td>AQ</td>
<td>Autism Spectrum Quotient</td>
</tr>
<tr>
<td>CE</td>
<td>Congruency Effect</td>
</tr>
<tr>
<td>CCT</td>
<td>Crossmodal Congruency Task</td>
</tr>
<tr>
<td>cm</td>
<td>Centimetre</td>
</tr>
<tr>
<td>DSM-IV</td>
<td>Diagnostic and Statistical Manual of Mental Disorders (4th edition)</td>
</tr>
<tr>
<td>EEG</td>
<td>Electroencephalography</td>
</tr>
<tr>
<td>EHI</td>
<td>Edinburgh Handedness Inventory</td>
</tr>
<tr>
<td>EPF</td>
<td>Enhanced Perceptual Functioning</td>
</tr>
<tr>
<td>ERP</td>
<td>Event Related Potential</td>
</tr>
<tr>
<td>fMRI</td>
<td>Functional Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>GSQ</td>
<td>Glasgow Sensory Quotient</td>
</tr>
<tr>
<td>hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>IQ</td>
<td>Intelligence Quotient</td>
</tr>
<tr>
<td>JND</td>
<td>Just Noticeable Difference</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>MAP</td>
<td>Maximum A Priori</td>
</tr>
<tr>
<td>MLE</td>
<td>Maximum Likelihood Estimation</td>
</tr>
<tr>
<td>mm</td>
<td>Millimetres</td>
</tr>
<tr>
<td>ms</td>
<td>Millisecond</td>
</tr>
<tr>
<td>NT</td>
<td>Neurotypical</td>
</tr>
<tr>
<td>PET</td>
<td>Positron Emission Tomography</td>
</tr>
<tr>
<td>PEST</td>
<td>Parameter Estimation by Sequential Testing</td>
</tr>
<tr>
<td>PLATO</td>
<td>Portable Liquid crystal Apparatus for Tachistoscopic Occlusion</td>
</tr>
<tr>
<td>PSE</td>
<td>Point of Subjective Equality</td>
</tr>
<tr>
<td>PSS</td>
<td>Point of Subjective Simultaneity</td>
</tr>
<tr>
<td>RSD</td>
<td>Root Squared Difference</td>
</tr>
<tr>
<td>RT</td>
<td>Reaction Time</td>
</tr>
<tr>
<td>SC</td>
<td>Superior Colliculus</td>
</tr>
<tr>
<td>SCS</td>
<td>Stochastic Cue Switching Model</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>SEM</td>
<td>Standard Error of the Mean</td>
</tr>
<tr>
<td>SJ</td>
<td>Simultaneity Judgement</td>
</tr>
<tr>
<td>SOA</td>
<td>Stimulus Onset Asynchrony</td>
</tr>
<tr>
<td>SPL</td>
<td>Sound Pressure Level</td>
</tr>
<tr>
<td>TA</td>
<td>Tactile-Auditory</td>
</tr>
<tr>
<td>TOJ</td>
<td>Temporal Order Judgement</td>
</tr>
<tr>
<td>VT</td>
<td>Visual-Tactile</td>
</tr>
<tr>
<td>WASI</td>
<td>Weschler Adult Scale of Intelligence</td>
</tr>
<tr>
<td>WCC</td>
<td>Weak Central Coherence</td>
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Abstract
How do people with autism process multisensory information?
Daniel Poole, the University of Manchester
For the Degree of Doctor of Philosophy (PhD)
30th September, 2015

Our experience of the world is based on information received from multiple sensory sources. To create a coherent representation of our environment, information from the different senses is combined to maximise the reliability of the combined percept. Furthermore, only stimuli occurring together in time and space will typically interact. Ineffective multisensory processing has been proposed as a possible explanation for the sensory differences experienced by many people with Autism Spectrum Condition (ASC). However, studies to date have produced mixed findings and have generally focused on the interaction between the visual and auditory modalities. The aim of the work presented in this thesis was to improve the characterisation of multisensory processing in adults with ASC, exploring the interaction between vision and touch for the first time. Specifically, we compared the temporal and spatial limits of multisensory processing, and the optimal combination of multisensory cues between participants with ASC and matched controls.

In Experiment 1, performance on a visual–haptic size judgement task was compared to predictions from a statistically optimal model in which unisensory cues are combined additively with the weight of each cue determined by its reliability. For both participants with ASC and controls, multisensory performance differed from the predictions of this optimal model, but was similar to a non-optimal model in which participants switch stochastically between cues from trial-to-trial.

The commonly used crossmodal congruency task was adapted for exploring individual differences in visual-tactile interactions. This task was used to explore the temporal modulation of visual distractors on tactile judgements (Experiment 4). Similar to controls, participants with ASC exhibited interactions only for simultaneous stimuli. Experiment 6 further explored uni and multisensory temporal sensitivity across vision, touch and hearing. No between group differences were observed, suggesting that the temporal processing of crossmodal stimuli is typical in adults with ASC.

The spatial limits of visual–tactile interactions were also investigated. A visual distractor positioned far from the stimulated hand influenced tactile judgements in the group with ASC, but not in controls (Experiments 5 and 8). However, this reduced spatial modulation was not observed for purely visual judgements (Experiment 9), and both groups of participants benefited from spatial separation in an alternate visual-tactile task (Experiment 7). These findings suggest that visual- tactile selective attention is affected in ASC.

This work has improved the characterisation of multisensory processing in ASC including a number of previously unexplored processes. It is hoped that work of this nature might ultimately lead to the development of effective sensory interventions for people with ASC.
Declaration

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Dedications

This work is dedicated to Vinay who inspired my interest in autism, and to my friend Jack.
Acknowledgements

Firstly, I must say a huge thank you to my supervisors: Ellen Poliakoff, Emma Gowen and Paul Warren. I could not have asked for a better team to work with. They have balanced supporting me and pushing me forward in a way that has been invaluable for my academic development. I am grateful to them for having given me the opportunity to work on this project.

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Finally, I would like to thank everyone who took part in the experiments reported in this thesis. I know that for many participants visiting the University could be a daunting experience. Their contribution to improving our understanding of autism must be acknowledged.
Chapter 1
General Introduction
'I make this noise when there is too much information coming into my head from the outside world. It is like when you are upset and you hold the radio against your ear and you tune it halfway between two stations so that all you get is white noise and then you turn the volume right up so that this is all you can hear and then you know you are safe because you cannot hear anything else'.


1.1. Preface
Our experience of our environment is based on the external senses of vision, hearing, touch, taste and smell. However, our senses do not work in isolation and perception is multisensory in nature. In the last 30 years, there has been growing interest in the processes by which information from the different senses interact. The work presented in this thesis explores a number of aspects of multisensory processing and how these may be affected in adults with autism spectrum condition (ASC).

A central tenet of multisensory processing is that using information from multiple sensory sources provides a more reliable estimate than using any one sense alone (Alais, Newell, & Mamassian, 2010). However, in many different scenarios a given sense may provide a more reliable estimate than others. For example, if a friend visits your house for a quiet cup of tea listening to them will involve combining the sound of their voice with the simultaneous sight of their lip movements. If you were to meet that friend in the clamour of a crowded bar, it might become more important to watch the movement of their lips to understand what was being said. This poses an interesting question in multisensory research: How does the brain weight the contribution of each sense to a combined percept to provide the most reliable estimate?

Another important challenge for the brain is determining which sensory signals originate from which sources. For instance, it would not help the conversation in the crowded bar if you believed the clink of empty pint glasses was generated by your friend’s lip movements. Thankfully, the brain does a good job of maintaining a stable multisensory percept of our surroundings. This is despite the noise inherent in our environment and that generated neuronally (Stein, Stanford, & Rowland, 2014). To increase the likelihood that information originating from the same source is combined, the interaction between the senses is based on the rules of spatial and temporal coincidence. This gives that information received by each of our senses at approximately the same time and in approximately the same space are more likely to interact.

The contribution that individual senses make to a combined percept and the limits of multisensory interactions in time and space were investigated in this thesis using a
number of behavioural experiments. We explored how these processes might differ between individuals with ASC and neurotypicals (NT). Many people with ASC experience atypical sensory processing (Crane, Goddard, & Pring, 2009; Kern et al., 2006), which can have a profound effect on their lives. However, the aetiology, and exact nature, of these differences is currently unknown. Improving the characterisation of multisensory processing in ASC will contribute to our understanding of these differences. This general introduction provides an overview of ASC and multisensory processing, providing justification for the experiments that follow.

1.2 Autism spectrum conditions
ASC refer to a class of complex neurodevelopmental conditions which occur in approximately 1% of the population (Baio, 2012; Baird et al., 2006; Gillberg, Cederlund, Lamberg, & Zeijlon, 2006; Scott, Baron-Cohen, Bolton, & Brayne, 2002). ASC is diagnostically characterised by a ‘triad’ of impairments (Wing & Gould, 1979; Wing, 1969). This triad describes impairments in social interaction and communication, plus restricted or repetitive patterns of behaviour. Impairments in social interaction include problems developing and maintaining friendships and atypical use of non-verbal cues such as eye contact and gesture. Communication impairments include delays in language development, difficulties sustaining conversations and echolia (parroting phrases). Repetitive or restricted patterns of behaviour can include strict adherence to routine, abnormally focused interests and repetitive movements such as rocking back and forth (Attwood, 2008; Frith, 2003). There are also a number of other impairments, and unique abilities, associated with ASC which are not captured by the diagnostic triad. These include differences in sensory and perceptual functioning (Mottron & Burack, 2001; Simmons et al., 2009), motor abnormalities (Gowen & Hamilton, 2013), and good rote memory (Frith, 2003). ASC is widely considered to be a spectrum condition due to its heterogeneous presentation. For example, communication impairments can span from a complete lack of verbal communication, despite speech being intact (‘selective mutism’), to unusual choice of words and phrases (‘stereotyped speech’). There is some debate as to whether the phenotype of autism is in fact more fractured than captured by current diagnostic criteria. It has been suggested that each aspect of the triad may represent discreet, but overlapping conditions (Coleman & Gillberg, 2012; Happé & Ronald, 2008). ASC is a lifelong condition, although in a minority of cases symptoms will improve and the individual may no longer reach the criteria for diagnosis in adulthood (Gillberg, 1991).
The latest diagnostic criteria has reduced the triad into two central components describing communication and social disturbances, and restricted/repetitive behaviours (DSM-V; American Psychiatric Association, 2013). The DSM-V also removed the subgroups that were previously described in the DSM-IV, including Asperger’s syndrome and pervasive developmental disorder not otherwise specified (American Psychiatric Association, 2000). These changes were encouraged by difficulties in characterising these specific sub-groups, particularly as an individual may move between the diagnostic categories. However, the changes have been contentious in the autistic and scientific communities (Wing, Gould, & Gillberg, 2013). Unless otherwise specified, ASC will be used throughout this thesis to describe individuals with any diagnosis on the autistic spectrum.

There is an apparent gender imbalance in the diagnosis of ASC, frequently reported as a ratio of males with a diagnosis outnumbering females 4:1. This ratio is reduced in individuals within the low IQ range (Fombonne, 2003). It is believed that this imbalance may be the result of differences in presentation between males and females. In particular, females with ASC with an IQ in the typical range are likely to show fewer restricted behaviours than males and compensate for communication difficulties (Kopp & Gillberg, 2011), leading to fewer females being diagnosed.

1.3. Neural functioning/ connectivity
ASC is diagnosed behaviourally, but is understood to be the result of atypical neurodevelopment. The infant ASC brain appears to grow to full volume far more quickly than in NT children (Courchesne & Carper, 2003). Beyond two years of age, growth is believed to slow down which may compromise effective connections between frontal brain regions (Courchesne, 2004). Indeed, a number of studies have suggested that long range connectivity between specialised regions is reduced in adults with ASC, with local connectivity increased. For example, when completing a language comprehension task, adults with ASC exhibited reduced functional connectivity throughout the language system compared to NT controls (Just, Cherkassky, Keller, & Minshew, 2004). Similarly, reduced connectivity between frontal-parietal regions have been observed when completing a non-verbal task assessing executive functioning (the Tower of London; Just, Cherkassky, Keller, Kana, & Minshew, 2007). The suggestion is that reduced connectivity is likely to lead to less integration of information between specialised brain regions. Furthermore, resting state functional magnetic resonance imaging (fMRI) has revealed reduced connectivity between a number of anterior and posterior areas in ASC (Cherkassky, Kana, Keller, & Just, 2006) and increased local
connectivity in a number of occipital and temporal regions (Itahashi et al., 2015). This indicates that issues with connectivity are pervasive and not only related to performance on cognitive tasks. Corpus callosum volume is reduced in individuals with ASC (see Frazier & Hardan, 2010), and is associated with symptom severity (Prigge et al., 2013). Similarly, inter-hemispheric correlations between brain regions are reduced in ASC, suggesting that connectivity across the corpus callosum is reduced (Anderson et al., 2011). Note that although reduced long range neural connectivity has been widely reported in ASC, increased connectivity between brain regions has also been observed which may reflect reduced synaptic pruning (see Müller et al., 2011).

1.4. Cognitive theories of autism
Numerous theories have been put forward in an attempt to describe the patterns of cognitive strengths and weaknesses that characterise ASC. A few of the more general theories are briefly summarised below.

1.4.1 Weak central coherence
Weak Central Coherence (WCC; Frith, 2003) is an influential theory of cognitive processing in ASC. Central coherence refers to an individual’s ability to combine local details into an integrated, global whole. Therefore, WCC describes a propensity to focus on local details while struggling to integrate global context. This theory was developed from observations of superior performance on a number of visuospatial tasks in ASC. Performance is faster on the embedded figures test (see Figure 1.1), in comparison to NT controls (Joliffe & Baron-Cohen, 1997; Shah & Frith, 1983). WCC suggests that the participants with ASC were able to extract the local detail (for example, the triangle in Figure 1.1) as they were less influenced by the overall context of the display (the pram). Individuals with ASC also show superior performance on visual search tasks in which a target must be detected amongst distractor items (O’Riordan, Plaisted, Baron-Cohen, Driver, & Baron-Cohen, 2001; Plaisted, Riordan, & Baron-Cohen, 1998). WCC was proposed to account for both atypical visuospatial performance and higher level social and semantic behaviour in ASC. This was supported by the observation that children with ASC were unable to integrate the context of a sentence to identify the correct pronunciation of a homograph (Happé, 1997).
The temporal binding hypothesis (Brock, Brown, Boucher, & Rippon, 2002) was put forward to explain the neural mechanisms which underlie the processing abnormalities of WCC. This theory suggests that poor connectivity between specialised brain regions leads to less synchronous firing of neurons and reduced integration of local information. This in turn leads to local details being represented in a hierarchical fashion rather than globally. The authors propose that binding within local regions may even be enhanced in ASC, resulting in the apparent preference for local processing.

There are a number of contradictory studies which have shown that the global processing is intact in ASC. A version of the Navon experiment (Navon, 1977, Figure 1.2), which requires an individual to process either the local or global details of a figure to detect a target letter, indicated that participants with ASC displayed a global processing advantage (Mottron, Burack, Stauder, & Robaey, 1999). A number of other visuospatial and semantic tasks have revealed no deficit in global processing (e.g. Caron, Mottron, Berthiaume, & Dawson, 2006; Lopez & Leekam, 2003). Moreover, the concept of central coherence is poorly defined in the NT population, making it difficult to make inferences about WCC in ASC (Pellicano, 2012).
1.4.2 Enhanced perceptual functioning

The enhanced perceptual functioning model (EPF; Mottron & Burack, 2001) was also developed to explain superior performance on certain low-level perceptual tasks in ASC. In this account, individuals with ASC have intensified perceptual processing. This leads to superior performance on certain tasks which require local processing, but also to detriments such as hypersensitivity to certain sensory stimuli (Baranek, David, Poe, Stone, & Watson, 2006), and a disruptive influence of perception on higher level cognition (Mottron, Dawson, Soulies, Hubert, & Burack, 2006). Unlike WCC, this theory does not posit that people with ASC have a deficit in global processing, but are less obliged to use global processing than NT participants.

1.4.3. Atypical executive functioning

Executive functioning is a broad term used to describe a number of aspects of cognition that are associated with prefrontal regions of the cortex. These functions are important in the control of complex behaviours and include planning, flexibility and the control of impulsivity (Burgess, 1997). The theory of ASC as an dysfunction in executive control developed from observations that the patterns of behaviour exhibited in ASC are similar to patients with frontal lobe lesions (Hill, 2004). Thriving on predictable routine, engaging in repetitive behaviour and an inability to control impulsivity are frequently reported as aspects of the experience of people with ASC. These are instances of behaviours that might be side products or compensatory strategies for disturbance in executive functioning. A number of early studies indicated that individuals with ASC perform poorly on the Wisconsin card sorting task, which tests cognitive flexibility (Rumsey & Hamburger, 1988, 1990). However, alternative tests of flexibility have revealed mixed patterns of performance in ASC (Hill & Bird, 2006). Participants with ASC perform more poorly than controls on tasks which involve planning such as variants of
the Tower of London task (Sinzig, Morsch, Bruning, Schmidt, & Lehmkuhl, 2008). Aspects of memory, such as working memory, which are believed to be components of executive functioning are impaired in ASC, while long term memory ability is intact, or superior (Bennetto, Pennington, Rogers, Pennington, & Rogers, 2015. Although see Edgin & Pennington, 2005). These findings point to a number of specific executive functioning impairments in ASC rather than a generalised deficit. Furthermore, the concept of executive functioning is quite broadly defined in the NT literature which impacts on the value of this theory in explaining cognition in ASC.

1.4.4. Broken mirror theory
Imitation is important in development by enabling social learning and bonding. Mirror neurons are populations of neurons in premotor areas which are activated by both a performed action and the observation of an action (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996), and are believed to be important in imitation. A number of studies have indicated that imitation skills are affected in ASC (e.g. Rogers et al., 1996). This has led to the suggestion that ASC is characterised by a defective mirror neuron system (Williams, Whiten, Suddendorf, & Perrett, 2001). However, there does not appear to be a generalised imitation impairment in ASC. Reduced automatic imitation of meaningless gesture is often observed, while intentional, goal directed imitation may be typical. For instance, individuals with ASC produce less muscle responses congruent with viewed facial expressions than controls, but perform typically when explicitly instructed to copy the expression (McIntosh, Reichmann-Decker, Winkielman, & Wilbarger, 2006). Typical imitation on automatic tasks has also been reported (Gowen, Stanley, & Miall, 2008; Hamilton, Brindley, & Frith, 2007). Furthermore, it has been suggested that the deficits in imitation do not necessarily represent a dysfunctional mirror system. Knowing when, and how, to imitate behaviours is a nuanced social behaviour that is likely to rely on a number of cognitive processes (Southgate & Hamilton, 2008). The current understanding of mirror neurons in humans has recently come under criticism (see Hickok, 2014). It has been suggested that the mirror neuron system cannot be solely responsible for the array of higher level cognitive functions which have been attributed to it, and many studies suffer from poor experimental design, lacking appropriate control conditions.

Although all these theories have generated hypotheses which have improved our understanding, there is no theory which has successfully captured the detailed cognitive profile of ASC. These theories share problems in providing a generalised approach to a highly heterogeneous condition and studies have produced variable findings. Rather
than attempting to confirm or falsify unifying theories of such a heterogeneous condition, it may be more worthwhile to focus on specific symptoms experienced in ASC (Happe, Ronald and Plomin, 2006). This thesis is focused on aspects of sensory functioning in ASC, which will be outlined below.

1.5. Sensory processing in ASC
Atypical responses to everyday stimuli have been reported since the first description of ASC (Kanner, 1943). Groupings of sensory dysfunction have since been identified: hyper sensitivity, hypo sensitivity and sensory seeking behaviours (Hazen, Stornelli, O’Rourke, Koesterer, & McDougle, 2014; Lane, Young, Baker, & Angley, 2010). Hypersensitivity describes an excessive negative association with stimuli, for example, an extreme sensitivity to the feeling of tags within clothing. Hyposensitivity describes the apparent unresponsiveness to particular stimuli, for example having a very high threshold for pain. Sensory seeking behaviours describe an excessive interest in sensory stimulation, for instance exploring inedible items in the mouth. Sensory atypicalities have been reported in all the senses in ASC. An individual may fluctuate between hyper and hypo responsiveness within, and between, the senses (O’Neill & Jones, 1997). Although sensory atypicalities are likely to impact on an individual’s life and are widely reported in ASC, they are not included in the diagnostic characterisation of the condition. Sensory symptoms are included as a sub-category of restricted and repetitive behaviours on the DSM-V, but are not considered a primary impairment as they are difficult to distinguish from sensory atypicalities reported in other conditions (Grapel, Cicchetti, & Volkmar, 2015). However, abnormal sensory behaviours are among the first clinically relevant features of autism, apparent before any language and communication difficulties can be observed (Dahlgren & Gillberg, 1989). Children with ASC can exhibit sensory behaviours that can distinguish them from those that develop typically, from as young as 18 months (Ben-Sasson et al., 2007).

Sensory atypicalities are widely reported and are believed to be present throughout an individual’s life. The majority of studies have used self-report (such as the Adult/Adolescent Sensory Profile, Brown & Dunn, 2002), or caregiver questionnaires (e.g. Dunn, 1999) to assess sensory functioning in ASC. Prevalence of sensory atypicalities is estimated at between 70-90% (Crane et al., 2009; Leekam, Nieto, Libby, Wing, & Gould, 2007; Tomchek & Dunn, 2007). A meta-analysis of care-giver questionnaire studies indicated that hypo-responsiveness is most frequently reported in ASC (Ben-Sasson et al., 2009). Atypical sensory processing is associated with a number of other features of autism. Strong relationships between repetitive behaviours and
hypersensitivity have been reported (Boyd et al., 2011; Gabriels et al., 2008). Sensory over responsiveness is believed to contribute to symptoms of anxiety, although discreet pathology is yet to be identified (Green & Ben-Sasson, 2010). Sensory atypicalities are associated with symptom severity in ASC, although this may be specific to children (Kern et al., 2007; Lane et al., 2010). Moreover, sensory symptoms are likely to impact on an individual’s day to day life, and are associated with reduced participation in activities (Little, Ausderau, Sideris, & Baranek, 2015).

As atypical sensory functioning can have a significant impact on the life of an individual with ASC, a number of sensory focused treatments have been developed. A large scale survey revealed 33% of children with ASC use ‘Sensory Integration Therapy’ (Green et al., 2006). This treatment is based on assumptions that interactive play with a number of sensory items (e.g. wearing a weighted vest) will lead to functional neural changes, resulting in a reduction in sensory symptoms (Roley, Mailloux, Miller-Kuhaneck, & Glennon, 2007). This link between the use of treatments and impact on neural functioning is currently speculative. Accordingly, there are few reports of effective outcomes from Sensory Integration Therapy (Baranek, 2002; Lang et al., 2012).

Improving our understanding of differences in sensory processing in ASC is important given the impact on the individual’s life and the widespread use of minimally effective sensory interventions. However, the studies described above generally used questionnaires which rely on the care-giver to interpret their child’s behaviours. Alternatively, studies rely on the descriptions of high-IQ adults with ASC, which can both skew the representation of sensory processing across the spectrum and be biased by the individual’s own recall of their experiences (O’Neil & Jones, 1997). A recent study employed a unique approach using videos to prompt children with ASC of ranging abilities to describe their experiences (Kirby, Dickie, & Baranek, 2015). The children revealed that they were averse to stimuli from multiple sensory sources and these experiences were liable to change over time. Many of the children in this study did not perceive these experiences as notably different to NT children. Although this study was exploratory it represents a novel approach to understanding sensory processing in ASC. In addition to qualitative and questionnaire studies, basic research is also essential to improve understanding of sensory and perceptual processes in ASC before effective interventions are likely to be developed.
1.6. Psychophysical research in ASC

Studies which have sought to characterise sensory functioning in ASC using experimental tasks are reviewed in this section.

1.6.1 Vision

Visual processing is the sensory modality which has been most extensively explored in ASC. Basic visual acuity is typical in people with ASC (Kéïta, Mottron, & Bertone, 2010). However, in line with WCC and EPF theories, there is evidence from a number of visual spatial tasks which indicate enhanced local processing in ASC, which may be at the expense of higher level integration of visual information. This has been the focus of the majority of visual research in ASC (see Dakin & Frith, 2005; Simmons et al., 2009 for comprehensive reviews of visual studies in ASC).

Evidence from neuroscientific and psychophysical studies have indicated that the visual system works in a hierarchical manner (Marr, 1982). Neurons early in the visual pathway are primarily activated for low level visual information with the integration of more complex visual information primarily processed later in the pathway (Felleman & Essen, 1991; Hubel & Wiesel, 1968). Pre cortical visual functioning appears to be intact in ASC. Flicker perception thresholds are comparable between participants with ASC and controls (Bertone, Mottron, Jelenic, & Faubert, 2005; Davis, Bockbrader, Murphy, Hetrick, & O'Donnell, 2006; Pellicano & Gibson, 2008). Aspects of visual performance in response to simple contour defined stimuli is also intact in ASC (Caron et al., 2006; although see Jachim, Warren, McLoughlin, & Gowen, 2015). However, colour processing may be affected in ASC. Children with ASC were less accurate than controls in identifying blue and green colour targets on colour background (Franklin, Sowden, Burley, Notman, & Alder, 2008). Children with ASC also performed more poorly than controls on a colour identification task (Heaton, Ludlow, & Roberson, 2008). More complex visual processing may be affected in ASC and global motion coherence studies have implicated a dorsal stream functioning deficit (Spencer et al., 2000). The participant views a field of coherently moving dots against a background of randomly moving dots and is asked to indicate the direction of the apparent movement, a staircase procedure is used to determine the participants 75% threshold for proportions of coherently moving to randomly moving dots. Children with ASC have produced significantly higher dot coherence thresholds than NT controls (Milne et al., 2002; Pellicano, Gibson, Maybery, Durkin, & Badcock, 2005; Spencer et al., 2000). However, a number of studies have found no differences in thresholds (Del Viva, Igliozzi, Tancred, Brizzolara, 2006; Manning, Charman, & Pellicano, 2015). It has recently been noted that
deficiencies in performance on global motion tasks in ASC may be dependent on a number of stimulus parameters. An fMRI study observed no motion processing deficits in adults with ASC for longer presentation durations, but deficits were present when the duration was 200ms. Differential brain activity was reported in all brain areas when the dots were presented for shorter durations, including primary visual areas (Robertson et al., 2014). Children with ASC produced higher thresholds than controls when the stimuli were presented in the central visual field, but not in the peripheral visual field, implicating visual spatial attention in observed deficiencies (Ronconi et al., 2012). Furthermore, children with ASC show no deficit where the dots are moving quickly, but differences between the groups are observed when the dots move slowly (Manning, Charman, & Pellicano, 2013). Although visual research in ASC has focused on local versus global processing for many years there is still contradictory evidence. The fact that findings differ with task demands, suggests that other cognitive processes may be relevant to atypical visual processing in ASC including attention and the perception of time.

1.6.2 Auditory
Abnormalities in auditory processing are among the most frequently reported sensory issues by individuals with ASC (Tomchek & Dunn, 2007). A number of studies have suggested people with ASC have superior pitch discrimination abilities which may relate to superior musical abilities in some with the condition (Mottron, Peretz, Belleville, & Rouleau, 1999). Adolescents and young adults with ASC performed better than controls on both a pitch discrimination task and pitch categorisation tasks when responding to pure tones (Bonnel et al., 2003). This has been supported by the observation that children with ASC are quicker than controls to identify when tones of varying frequency between 750-6,000hz are adjusted to the same pitch as a standard tone (O’Riordan & Passetti, 2006). Children with ASC also show superior performance to controls on tasks requiring the identification of pitch using verbal stimuli (Heaton, Hudry, Ludlow, & Hill, 2008). There is evidence, however, that superior pitch sensitivity may be confined to a subgroup of individuals with ASC. Exceptional frequency discrimination (two standard deviations (SD) above the control group mean) was associated with higher IQ and delayed language development in ASC (Jones et al., 2009). This suggests there is a link between low-level perceptual abilities and higher level functioning. There is also some evidence of hyperacusis (over sensitivity to particular frequencies and volumes) in children with ASC. Pure tones were rated as loud at lower dB intensity in comparison to NT controls (Khalfa et al., 2004), despite thresholds for loudness
perception being comparable between the groups. Similarly, children with ASC reported being unable to tolerate clicks presented at lower volumes than NT controls (Rosenhall, Nordin, Sandstrom, Ahlsen, & Gillberg, 1999).

1.6.3. Other sensory modalities
As for the NT psychophysical literature, the other senses have not been investigated as extensively as vision and audition in ASC. Studies of touch have revealed that adults with ASC have lower detection thresholds for 200Hz vibrations than controls (Blakemore et al., 2006). However, this effect was not replicated in children with ASC (Güçlü, Tanidir, Mukaddes, & Unal, 2007). Cascio et al. (2008) utilised a battery of psychophysical tasks to explore aspects of tactile processing on the finger and forearm in adults with ASC. Thresholds for the detection of pressure and vibrotactile stimuli on the finger were similar between the groups. Participants with ASC produced lower thresholds for vibrotactile detection presented to the forearm. Stimulation of the forearm is believed to be detected by the Pacinian corpuscles which are also stimulated by high frequency vibration. Participants with ASC also produced reduced pain thresholds for cooling temperature. These studies suggest that sensitivity to afferent somatosensory systems is increased in ASC. However, the few studies which have investigated tactile processing in ASC have worked with relatively low sample numbers (n < 10), and further work is required to improve the characterisation of basic tactile processing in the condition.

Very few studies have attempted to investigate olfactory and gustatory processing in ASC. Reduced detection of odours (level of dilution) has been reported in ASC compared to controls (Dudova et al., 2011). However, there were no between group differences in the identification of odours (see also Brewer, Brereton, & Tonge, 2008). Contradicting this, adolescents with ASC produced reduced odour identification, which was associated with aspects of social functioning (Bennetto, Kuschner, & Hyman, 2007). Taste identification was also explored in this study. The ASC group were worse than controls at identifying citric flavour, while other flavours were comparable. A study in adults revealed reduced taste identification in participants with ASC overall, particularly sour, sweet and bitter tastes. Participants in this study tended to misidentify tastes as being salty, or as having no flavour (Tavassoli & Baron-Cohen, 2012).

Although interest in sensory perception in ASC is increasing, findings are mixed. Sensory abnormalities are reported in each modality and represent a significant aspect of the experiences of people with ASC. However, psychophysical studies have produced extremely variable findings. As a number of the senses have been reported to be
affected in ASC, researchers have become interested in the interaction between the senses. The following section will provide an overview of multisensory processing.

1.7. Multisensory integration

1.7.1. Animal studies

Our understanding of the interaction between the senses developed from the pioneering working of Stein and colleagues investigating the superior colliculus (SC) in cats (see Stein, Stanford, & Rowland, 2014; Stein & Stanford, 2008 for reviews). The SC is a midbrain structure which had previously been identified as important in attention to visual, auditory and somatosensory stimuli (Stein & Meredith, 1990). The SC is in fact a site of convergence for inputs from visual, auditory and somatosensory cortices, and many multisensory neurons were identified in this region. Multisensory neurons produce a greater evoked response to multisensory stimuli than any single sense alone (Meredith & Stein, 1983). There is a super additive effect, such that the response generated from the multisensory stimulus will often exceed the sum of the unisensory responses. This is referred to as multisensory integration. Stein and Meredith’s work in the SC led to three defining rules of multisensory integration being developed: the rules of inverse effectiveness and a spatial and temporal rule. Figure 1.3 gives a schematic overview of multisensory integration.

Figure 1.3 Overview of the neural process of multisensory integration and the analogous behavioural processes observed in studies of multisensory interactions.
The greatest multisensory response enhancement is observed when two weaker unisensory responses are integrated. Stimuli presented to each modality which evoke a stronger response in isolation will lead to less multisensory enhancement. The proportional response of multisensory integration is inverse to the relative efficacy of the integrated cues, hence inverse effectiveness (Meredith & Stein, 1986a).

The neural response for the location of a stimulus is represented by a cell’s spatial receptive field. A number of the multisensory neurons in the SC have been observed to have overlapping receptive fields (Meredith & Stein, 1986b). That is, a cell’s response can be elicited by stimuli presented to different sensory modalities when located within the representation of that cell’s receptive field. The overlapping spatial fields of multisensory cells ensure that sensory stimuli which originate from the same source interact in the same region of the SC. This also ensures that the sensory topographies map onto motor topographies to enable co-ordinated motor response to sensory input (Stein & Meredith, 1990). Similarly, maximum response follows from the temporal coincidence of two stimuli (Meredith, Nemitz, & Stein, 1987). However, there was a degree of separation between the stimuli over which integration would continue to be observed. A bias towards visual stimulus preceding the auditory was also observed in response enhancements. The range of stimulus onset asynchronies (SOA) over which this response enhancement was observed was referred to as the temporal window of integration. If stimuli do not occur within the spatial receptive field of a cell, or the temporal window the stimuli are not integrated. Accordingly, no response enhancement is observed, or one stimulus may inhibit the cells response to the other stimulus (Kadunce, Vaughan, Wallace, Benedek, & Stein, 1997). This is likely to reduce the possibility of unrelated sensory stimuli being integrated.

Multisensory integration appears to follow a developmental trajectory (Stein et al., 2014; Wallace, 2004). In the early years of a cat’s life, there are no multisensory cells observed in the SC (Wallace and Stein, 1997). When presented with crossmodal stimuli, the response is equivalent to that generated by the greatest unisensory response, suggesting that stimuli are not integrated. The proportion of multisensory cells in the SC increases from four weeks in age, until reaching adult levels by twelve weeks. Multisensory integration develops through experience of crossmodal stimuli (Yu, Rowland, & Stein, 2010). Developing multisensory cells have enlarged receptive fields and multisensory integration will be observed when crossmodal stimuli are separated in
space and time. The windows for binding contract over development (Wallace and Stein, 1997).

1.7.2 Multisensory integration in humans
Subsequent advances in neuroscience have allowed analogous neural activity to be observed in human beings. Calvert, Hansen, Iversen and Brammer (2001) presented participants with visual stimuli that changed colour in synchrony with auditory noises. The SC exhibited the greatest multisensory enhancement in response to crossmodal stimuli. The posterior parietal region is a cortical area involved in spatial awareness where a number of unisensory inputs converge. A number of primate studies have revealed that large populations of multisensory neurons are found in this region (e.g. Gentilucci et al., 1988). Subsequent fMRI studies have revealed analogous activity in humans (Bremmer et al., 2001). When participants were presented with simultaneous visual, auditory and tactile stimuli neural activity increased in a number of deep parietal regions. In a study of event related potentials, participants identified simple visual and auditory stimuli (Giard & Peronnet, 1997). Participants Reaction Times (RT) were increased in response to crossmodal stimuli, indicating a behavioural multisensory performance enhancement. Audio-visual interaction components were identified by deducting the unisensory ERP responses from the combined. The greatest of these interaction effects was observed in the right fronto-temporal region.

These studies indicate that the integration of multisensory stimuli is associated with higher cortical levels of activation in human beings, analogously to animal studies. However, multisensory effects have been observed in primary sensory areas, which were previously believed to be unisensory. Recent animal studies have revealed there is a complex network of connections between primary sensory areas (see Schroeder & Foxe, 2005). Similarly, multisensory activity has been reported in unisensory areas in humans. For instance, positron emission tomography (PET) scanning has revealed that early visual areas are activated when making judgements about ridges using only touch (Sathian & Zangaladze, 2002). Activity is observed in area V1 following tactile stimulation (Macaluso, Frith, & Driver, 2000). Moreover, multisensory integration has been observed in primary sensory areas. An fMRI study of the auditory cortex revealed that simultaneous auditory and somatosensory stimulation resulted in greater activation than the sum of the individual responses (Foxe et al., 2002). This suggests that multisensory integration involves complex interactions between higher and lower level neural processing and, perhaps, that no unisensory information is processed truly independently (Schroeder & Foxe, 2005).
In summary, multisensory integration involves the integration of information from specialised neural areas. Multisensory processing has been observed in high and low level neural regions. Effective multisensory integration matures through development.

1.8. Multisensory perception
Behavioural performance which is analogous to these neural markers of multisensory integration has been widely reported. As this thesis is centred on behavioural investigations of multisensory interactions, key studies will be introduced in greater depth before the relevant chapter. However, an overview of some principle concepts is included below.

1.8.1. Multisensory performance enhancement
The interaction between the senses leads to a number of behavioural performance enhancements. For instance, RTs are typically reduced for crossmodal stimuli. Performance in response to crossmodal stimuli can be compared to the predictions of a race model (Raab, 1962). The race model provides a prediction of performance whereby information received by each sense is processed separately, with the fastest individual signal to be processed leading the response. Accordingly, when the responses in the multisensory condition are faster than the model predictions (the race model is violated), it is assumed that the signals have interacted (Miller, 1982). The performance enhancement observed for race model violations might be considered a behavioural analogue to the super additive neural response observed in multisensory cells.

The speed of eye movements towards a visual target can be enhanced when presented with simultaneous, task irrelevant crossmodal stimulation. Participants were instructed to look at a simple visual target while ignoring auditory tones (Colonius & Arndt, 2001; Hughes, Nelson, & Aronchick, 1998). Saccadic latencies were significantly reduced in audio-visual trials in comparison to vision alone when the tone was in close spatial and temporal proximity with the visual targets. A similar reduction in saccadic latencies was observed when presented with coincident tactile cues (Amlôt, Walker, Driver, & Spence, 2003). Furthermore, task irrelevant, non-informative cues have been shown to improve performance on visual search tasks. Participants searched for a horizontal or vertical target amongst a large array of distractor lines (Van der Burg, Olivers, Bronkhorst, & Theeuwes, 2008). The lines in the array continuously changed colour throughout the task, with the target colour changing independently to the distractors. On audio-visual trials, an auditory tone was presented simultaneously with the target colour change, significantly reducing RTs and error rate in comparison to visual alone trials. There were similar findings when the task irrelevant stimuli were tactile (Van der Burg, Olivers,
Bronkhorst, & Theeuwes, 2009). It is important to note that the auditory and tactile stimuli in these experiments provided no information about the orientation or location of the target. This effect has been attributed to multisensory information increasing the salience of the visual cue.

Performance on several multisensory tasks (e.g. Ernst & Banks, 2002; Alais & Burr, 2004) is predicted by a statistically optimal maximum likelihood estimation (MLE) model, in which unisensory cues are combined with the weight of each cue determined by its variance. A multisensory performance enhancement is observed as this combination rule ensures that variance in the multisensory estimate is minimised. Studies exploring optimal cue-integration are described in detail in Chapter 2.

1.8.2. Multisensory illusions
The interaction between the senses is thought to be automatic. In an attempt to maintain a stable percept, inconsistent multisensory cues may interact which can be exploited to create multisensory illusions. A non-experimental example is the ventriloquist’s stage act whereby a lifeless dummy can be made to appear to talk when its lips are seen to move at the same time as the ventriloquists’ voice. The McGurk task (MacDonald & McGurk, 1978) is a behavioural task which similarly relies on the automatic interaction between what is heard and seen. Participants are presented with a video clip of a mouthed syllable (for instance ‘ga’) with an audio track pronouncing an incongruent syllable (‘ba’). When the participant is asked what the speaker is saying they will frequently report an entirely new syllable (such as ‘da’). Similar findings have been produced on audio-visual tasks which do not involve verbal stimuli. Where participants are asked to make judgements about the number of visual flashes, they typically produce responses consistent with having seen multiple flashes if multiple beeps are presented simultaneously (the flash beep illusion; Shams, Kamitani, & Shimojo, 2000; Shams, Kamitani, & Shimojo, 2002). Visual-tactile interactions are commonly investigated using the crossmodal congruency task (CCT; Spence and Driver, 1998). Participants make speeded judgements regarding whether their finger or thumb has been stimulated by a vibrotactile pulse, while ignoring distractor light flashes presented either by the finger or thumb. Distractors presented in close spatial and temporal proximity to the stimulated hand typically influence participant’s response to the tactile target. The CCT is described in greater detail in Chapter 3. The rubber hand illusion (Botvinick & Cohen, 1998) is a multisensory illusion created through the strength of interaction between visual, tactile and proprioceptive cues. Participants view a rubber hand being touched in synchrony with their own hand, which is concealed from
view. The participant often reports a convincing impression that the rubber hand is their own. Estimates of the location of their own hand may also be displaced towards the rubber hand, displaying the impact that the incongruent visual information can have on proprioception (Tsakiris & Haggard, 2005).

1.8.3. The role of attention in multisensory processing

There is a debate regarding the relationship between multisensory processing and crossmodal attention, and the specific levels of processing at which the two may interact (see Koelewijn, Bronkhorst, & Theeuwes, 2010 for a review). On one side it has been suggested that multisensory processing occurs prior to attention and captures attention through an increase in salience of the stimuli (an example of this is the Van der Burg et al., 2008, 2009 tasks discussed above). Furthermore, a sound presented with an imperceptible visual stimuli can cause that stimulus to be perceptible (Aller, Giani, Conrad, Watanabe, & Noppeney, 2015). Participants were presented with a target flash to one eye while presented with a mask, which reduced awareness of the flash. However when presented with a concurrent beep, the participants awareness of the flash increased. These studies suggest that the multisensory interactions occur at an early level of processing, prior to attention.

The alternative view is that attentional resources are required to enable the interaction between multisensory stimuli. For instance, the McGurk effect has been investigated under different attentional manipulations (Alsius, Navarra, Campbell, & Soto-Faraco, 2005). Participants completed the McGurk task while attending to repetitions in a concurrent visual stream (line drawing over the face), audio stream (simultaneous sounds), or with no attentional manipulation. Attending to visual or auditory stimuli had a significant negative effect on the proportion of McGurk responses. However, the attentional manipulations had no effect on unisensory responses. This suggests that attentional resources are required for multisensory interactions. Effects of attention have also been reported on multisensory integration. Participants attended to a letter stream while presented with irrelevant audio-visual stimuli (Talsma, Doty, & Woldorff, 2007) and were either instructed to attend to the letter stream, audio-visual stimuli only or the unisensory stimuli only. ERPs were recorded to provide measures of multisensory integration for each attentional manipulation. Super additive effects were found when the audio-visual stimuli were attended to, while subadditive effects were observed when participants attended to the letter stream. This suggests that multisensory integration is reduced when attention is directed away from the stimuli. It is likely that the relationship between multisensory interactions and attention impacts on multiple
stages of processing (Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010). In certain contexts multisensory interactions may occur independently of attentional resources, while in other contexts attention may modulate multisensory processing. This remains an interesting area for research.

1.8.4 A note on nomenclature
As has been highlighted elsewhere (Stein et al., 2010) the multisensory literature contains inconsistent use of terminology. The term multisensory integration is frequently used to describe behavioural performance enhancements, or responses which are consistent with multisensory illusions. However, multisensory integration specifically refers to the super additive neural activity in response to crossmodal stimuli (e.g. Stein & Stanford, 2008). It is not always known whether performance on specific behavioural tasks maps onto neuronal integration of multisensory stimuli. Multisensory effects are likely to represent a number of cognitive processes including multisensory integration, attention and response strategy.

Throughout this thesis, multisensory processing will be used as a generic term to describe participant’s responses to stimuli from multiple sensory sources. Improvements in performance in response to crossmodal stimuli over unimodal stimuli will be referred to as multisensory performance enhancements. Any detriments in performance, or illusory responses, driven by crossmodal stimuli will be referred to as multisensory effects or multisensory interactions. The term cue combination is used in Chapter 2 to describe responses to cues presented to multiple sensory modalities, while cue integration is used where participant’s performance is consistent with a statistically optimal model (see Ernst and Bülthoff, 2004).

A number of studies which will be referred to later in this thesis (e.g. Foss-Feig et al., 2010) employ the term temporal binding window to describe the range of SOA over which multisensory effects may be observed. This is derived from the temporal binding window of integration (Meredith et al., 1987), which specifically refers to the range of SOA over which the super additive neuronal response which characterises multisensory integration is observed. Temporal modulation or temporal sensitivity will be used to describe relevant processes which are observed behaviourally.

1.9. Why study multisensory interactions in ASC
It has previously been suggested that multisensory processing may be relevant in the aetiology of sensory abnormalities in ASC (Iarocci & McDonald, 2006). There is increasing interest in characterising multisensory processing in ASC and existing studies
are reviewed in Chapters 4 and 5. The current overview highlighted a number of reasons why multisensory processing may be affected in ASC. Firstly, questionnaire studies and clinical observations have described a number of sensory and perceptual atypicalities in ASC. These differences appear to vary within and between individuals and have been reported across all of the senses. However, empirical research exploring unisensory perceptual processing in ASC has produced mixed findings to date. As our experience of the world is multisensory, it may be that sensory differences are the result of atypical multisensory interactions. For instance, a person with ASC may be sensitive to the bright lights of a car headlight, but this could be the result of atypical interactions between the sights, sounds and smells of a busy road. Second, ASC is a neurodevelopmental condition which is believed to be characterised by poor connectivity between specialised brain regions. Multisensory processing involves combining information across multiple specialised brain regions and may be disrupted by reduced neural connectivity in ASC. For instance, reduced long range connectivity in ASC which may lead to issues integrating information between networks (Anderson et al., 2011; Brock et al., 2002; Kikuchi et al., 2014). Similarly, classic cognitive theories of ASC have implicated the integration of local information into a global percept, a similar process to multisensory processing in which information from individual modalities interact to create a unified percept. Finally, effective multisensory processing matures through development. It seems plausible that abnormalities in neuronal development in ASC may have an impact on the maturation of multisensory processing.

1.10. The current investigation
The current investigation explored a number of aspects of multisensory processing in ASC, with a particular focus on the interaction between vision and touch. This was carried out over this thesis as follows:

The experiment reported in Chapter 2 investigated the contribution that each sense makes to a combined multisensory estimate. A number of studies have investigated the contribution of each sense to a combined percept in NT participants (e.g. Ernst & Banks, 2002). These studies have indicated that the more reliable sense is typically given greater weight in a multisensory estimate (see Chapter 2 for a more in depth introduction). A visual-haptic task was utilised to compare the performance of adults with ASC and NT controls to probabilistic models of performance previously established in the NT literature.
In Chapter 3, an existing paradigm (the crossmodal congruency task; Spence, Pavani, & Driver, 1998) was adapted for investigating the limits of visual-tactile in heterogeneous groups (e.g. ASC). This adapted paradigm was validated for measuring the temporal and spatial modulation of visual-tactile interactions (Experiments 2 and 3).

In Chapter 4, this newly developed paradigm was used to explore the temporal (Experiment 4) and spatial (Experiment 5) modulation of vision and touch in participants with ASC and a NT control group. The findings of these experiments were further explored and replicated in Chapters 5 and 6. In Chapter 5, temporal acuity was investigated within and between vision, touch and hearing in participants with ASC and NT. Chapter 6 reports the findings of a number of tasks exploring the representation of space in ASC, including the effect of space on multisensory temporal processing and attention (Experiments 7-9).
Chapter 2

Visual-haptic cue combination in adults with autism spectrum conditions

The research reported in this chapter has been presented at the following conference presentations:


2.1 Introduction
The Bayesian approach to perception has been an influential theory for understanding a number of aspects of cognition. This has provided some particularly strong insights into sensory processing. For example, research has explored optimal methods for combining information from different sensory modalities. This chapter begins with a review of Bayesian theory and its relevance for the combination of multisensory information. The results of an experiment investigating the contribution of two sensory modalities to a combined multisensory estimate, specifically visual and haptic (active touch) information are then described.

2.1.1. Bayesian perception
Bayesian probability theory has become a popular framework for understanding the organisation of sensory systems (Knill & Pouget, 2004). Briefly, Bayesian theory formalises how hypotheses (or belief about the world) should be updated given new information. If $S$ is a hypothesis and $I$ is the new evidence, Bayes theorem gives:

$$P(S/I) = \frac{P(I/S) P(S)}{P(I)}$$

Where $P(I/S)$ is the likelihood, which reflects the relative likelihood of obtaining the current evidence for the set of possible hypotheses. $P(S)$ is the prior, a probability distribution on possible hypotheses before having observed the new evidence and $P(I)$ is a probability distribution on the new evidence (this term is usually hard to obtain and is often overlooked since it represents a scaling factor). $P(S/I)$ is the posterior, a probability distribution on possible hypotheses given the data. The posterior distribution depends on both the prior and likelihood function, and its peak will move towards the less noisy distribution (see Figure 2.1).
Figure 2.1 Two example scenarios showing the movement of the posterior distribution depending on the variability associated with the prior and the likelihood. A: the variability associated with the prior is similar to that of the likelihood and the posterior distribution will fall half-way between the two. B: the prior is more variable and the posterior distribution is biased towards the likelihood. The variability associated with the posterior distribution is lower than either the likelihood or the prior.

When applied to visual perception (Yuille & Bülthoff, 1996), the hypotheses H represent states of the world to be inferred from visual data I. The likelihood function represents the likelihood of having obtained the particular visual data currently sensed given each possible state of the world. The likelihood reflects the processes of visual sensation under which data about the world are generated using the visual system. The peak of this function gives the most likely estimate of the stimulus given only the present data (i.e. ignoring any prior information). The likelihood is typically modelled as a Gaussian distribution centred on the true state of the world with variance reflecting the noise and ambiguity in visual processing.

In the context of visual perception, the prior can be thought of as the probability of each possible world state in the absence of any visual data (e.g. with the eyes closed). As such the prior is thought to reflect statistical regularities in the world derived from knowledge of our environment. For example, that light will tend to fall on the stimulus from above (Mamassian, Knill, & Kersten, 1998). Conversely, a uniform prior represents circumstances where all the possible states of the world are considered equally likely to occur. When likelihood and prior are combined using Bayes rule the posterior...
distribution provides a more reliable (i.e. less variable) estimate of the world than either the prior or likelihood alone. The peak of the posterior distribution gives the most probable state of the world and is referred to as the maximum a priori estimate (MAP). Crucially, as noted above the location of the peak will be closer to whichever of the prior or likelihood has lowest variance, i.e. whichever provides the most reliable information about the possible states of the world (with reliability given as $\frac{1}{\sigma^2}$). In the case of an uninformative uniform prior, it can have no influence on the peak of the posterior and the MAP is also the maximum likelihood estimate.

2.1.2. Cue integration
The above example describes a model of sensory estimation based on a single sensory cue. However, our perception of the world is based on the input of multiple cues within and between the senses. Yuille & Bülthoff (1996) describe two ways in which cues may be combined. If the cues are considered to be independent, then a MAP estimate $\hat{E}_i = \max (P[S|c_i])$ may be calculated for each of $N$ image cues, $c_i$, independently and then combined through averaging.

$$E = \frac{1}{N} \sum_{i=1}^{N} \hat{E}_i$$

This combination model is referred to as ‘weak fusion’. However, one problem with weak fusion is that when a particular cue is more variable than others, it will still make an equal contribution to the MAP estimate when averaged (Landy, Maloney, Johnston, & Young, 1995). Thus, allowing a less reliable estimate to have the same weight as more reliable estimates is likely to result in a sub-optimal combined estimate. Alternatively, if the cues are not considered to be independent then they should share a single likelihood function (‘strong fusion’). Strong fusion is problematic for sensory combination as any distinction between the cues is removed, despite the qualitative differences between cues for sensory estimates (e.g. binocular disparity and texture cues to depth).

An alternative ‘modified weak fusion model’ was formulated by Landy et. al (1995). Landy and colleagues consider the case of two cues $c_1$ and $c_2$ with separate posterior distributions $P[S|c_i]$ obtained using Bayes rule as described above. As a way to combine these distributions and take account of the relative reliability of each estimate, Landy et al suggested treating each posterior as an independent likelihood function on the states of the world. This is reasonable since the posterior measures the likelihood that each scene is the real scene. They then suggest these likelihood functions could be combined
by multiplication in Bayes rule, in a similar manner to the combination of the prior and likelihood. This ensures that the peak of the resultant distribution is biased towards whichever cue’s posterior has lower variance (similar to Figure 2.1). It also ensures that the resultant combined distribution has lower variance than either of the two individual posteriors.

Crucially, it can be shown under certain conditions (See Yuille & Bülthoff, 1996) that the resultant estimate \( \hat{E} \) obtained as the maximum of the product of the two Likelihood functions, (i.e. \( \hat{E} = \max(P[S|c_1]P[S|c_2]) \)) approximates the output of the linear combination rule which is optimal. This combination rule is commonly referred to as the Maximum Likelihood Estimate (MLE). The MLE is given by a combination rule as described by equation 1. The combined estimate \( E_{12} \) based on cues \( c_1 \) and \( c_2 \) is obtained using a weighted sum of the estimates \( (E_1, E_2) \) obtained from the individual cues (equation 1).

\[
E_{12} = w_1 E_1 + w_2 E_2 \quad (eq.1)
\]

The weight for each cue is related to its reliability (inverse variance) and sum to 1 (equation 2).

\[
w_1 = \frac{1/\sigma_1^2}{1/\sigma_1^2 + 1/\sigma_2^2}, \quad w_2 = \frac{1/\sigma_2^2}{1/\sigma_1^2 + 1/\sigma_2^2} \quad (eq.2)
\]

More reliable cues are given increased weight relative to less reliable information sources. The combined estimate is more reliable than that provided by either cue alone (Figure 2.2) and for the assumptions noted below is optimal in the sense of having highest reliability (lowest variance).
Figure 2.2 Two scenarios for the integration of cues 1 and 2 according to the MLE model (Ernst & Banks, 2002; Landy et al., 1995). In the first scenario (A) the variance associated with 1 and 2 is approximately equal. The weight for each cue is therefore approximately equal. The combined estimate $1 \hat{} 2$ has lower variance than either 1 or 2 and falls in between. In the second scenario (B) the variance associated with 2 is lower than 1. Therefore, 2 is given greater weight in the combined estimate and the combined estimate moves towards 2.

This MLE model makes two principle assumptions (Ernst & Bülthoff, 2004; Landy et al., 1995)

1. The cues that are combined are measuring the same property of a scene in the same units.
2. The estimates provided by each cue are corrupted by unbiased Gaussian noise and these noise sources are independent of one another.

2.1.3 Experimental studies investigating optimal multisensory cue integration
A number of studies have investigated sensory cue combination in humans both within and between the senses, and in particular whether humans use the MLE rule. As the combination of multisensory cues is relevant to the current paradigm this will be the focus of the discussion below.

2.1.3.1. Early theories of sensory dominance in multisensory estimates
The contribution of each sensory modality to a multisensory judgement has been explored extensively using cue-conflict paradigms (see Welch & Warren, 1980 for a
review). Participants typically make perceptual estimates regarding non-matching (conflicting) crossmodal stimuli. For instance, judging the size of blocks that are magnified so that they are perceived differently visually and haptically (Rock & Victor, 1964). In these conditions of cue-conflict, it is assumed that the perceptual system attempts to maintain a normal (non-conflict) percept. It is possible to determine bias towards either modality in the combined percept by comparing the participant’s multisensory estimate with the physical properties of either cue in the conflict. Early theories held that multisensory estimates were dominated by vision, with shape perception during visual-haptic conflict being closer to the visual cue (termed visual capture; Hay, Cuoghe, & Ikeda, 1965; Rock & Victor, 1964; Tastevin, 1937). However, it was subsequently noted that vision did not dominate in all multisensory judgements. Auditory information appears to dominate in multisensory temporal perception (Burr, Banks, & Morrone, 2009; Welch, Dutronhurt, & Warren, 1986), and touch in the perception of texture (Fishkin, Pishkin, & Stahl, 1975). An alternative account proposed that the sensory modality with the greatest reliability for a given task would dominate in conditions of crossmodal conflict (Welch & Warren, 1980).

2.1.3.2. Optimal cue integration
Subsequently the MLE model described in section 2.1.2 has been compared to human multisensory estimates using cue-conflict paradigms. In a seminal study, Ernst and Banks (2002) asked participants to make comparative height judgements of virtual reality bars: the visual stimuli were rendered using a random dot stereogram which created the impression of a raised bar when viewed through a stereoscope. Haptic stimuli were generated using force feedback devices which delivered pressure to the participant’s fingers to simulate the edges of the bar. Participants were presented with a standard stimulus, which was fixed in height, and a comparison stimulus, which was variable in height. They were asked to make two interval forced choice (2IFC) height judgements (which was taller?) using the method of constant stimuli, whereby the participant is repeatedly presented with a fixed set of stimuli in a random order.

The aforementioned assumptions of the MLE model were met in Ernst and Banks (2002), and in Experiment 1 as:

1. Sensory modalities are believed to be well calibrated in order to provide a coherent percept of one’s environment, meaning that the unisensory estimates will be unbiased
2. It is likely that the variance associated with each cue will be independent when presented to different sensory modalities (Oruç, Maloney, & Landy, 2003).

Performance was measured in separate visual and haptic unisensory conditions, and a dual modality condition in which participants were presented with the cues together. For each condition it was possible to fit a psychometric function to the size discrimination data and extract an estimate of the point of subjective equality (PSE) which represents bias in the participant’s percept, and a measure of variance (and thus reliability) in the sensory estimate (refer to Appendix A). It is then possible to derive the first MLE prediction which is based on the unisensory variance data and can be compared to the participant’s variance in the dual modality condition. Specifically, under MLE, the multisensory variance predicted using the combination rule described in equations 1 and 2 should be given by equation 3 where \( \sigma_v^2 \) gives the visual and \( \sigma_h^2 \) the haptic variance

\[
\sigma_{vh}^2 = \frac{\sigma_v^2 \sigma_h^2}{\sigma_h^2 + \sigma_v^2}
\]  
(eq.3)

As noted above, the MLE model provides a combined multisensory estimate that is more reliable than either of the unisensory estimates. It is statistically optimal as the visual and haptic estimates are combined in a manner which minimises the variance in the multisensory estimate (Figure 2.2).

The dual modality condition in Ernst and Banks’ experiment included trials in which visual-haptic stimuli were presented in conflict. Using this data it was possible to perform a second test of the MLE model. Specifically, by measuring whether the participant’s point of subjective equality (PSE) is biased towards the visual or haptic cue in the conflict conditions indicated which cue has greater weight. Furthermore it was possible to compare participant’s performance in each conflict condition with an MLE prediction of the PSE in each condition from equation 4

\[
E_{vh} = w_v E_v + w_h E_h
\]  
(eq. 4)

Here \( E \) denotes the estimate of size in each dual modality or unisensory condition. Based on eq. 2 the weights (\( w \)) were then calculated from the unisensory variance data according to equation 5.

\[
w_h = \frac{1/\sigma_h^2}{1/\sigma_h^2 + 1/\sigma_v^2} = \frac{\sigma_v^2}{\sigma_h^2 + \sigma_v^2}, \quad w_v = \frac{1/\sigma_v^2}{1/\sigma_h^2 + 1/\sigma_v^2} = \frac{\sigma_h^2}{\sigma_h^2 + \sigma_v^2}
\]  
(eq. 5)
Ernst and Banks found participant data was consistent with the MLE model for tests based on both reliability and bias in the multisensory estimates. First, multisensory variance was lower than that measured for either unisensory condition. Second, variance was lower for visual estimates than haptic and in accordance with equation 5, performance in the cue-conflict conditions showed a bias towards vision. In a further experiment, Ernst and Banks manipulated the reliability of the visual cue. Presenting the stimuli using a random dot stereogram meant that visual noise could be increased by jittering the dot positions. Again, in accordance with the MLE model participant haptic weights increased and their multisensory estimates were biased towards the haptic standard. This suggests that rather than the most appropriate modality for judgements about a particular stimulus dominating (as suggested by Welch & Warren, 1980), a multisensory estimate is driven by the most reliable (minimum variance) modality for that given estimate. That is, human performance on this visual-haptic task was well predicted by a statistically optimal MLE model.

The MLE model has subsequently shown to be a robust predictor of performance on a number of multisensory tasks. For example, performance on a visual-auditory position estimation task was well predicted by the MLE model (Alais & Burr, 2004). Participant’s indicated the spatial location of visual flashes, auditory clicks, or the two presented together. In unimodal condition the variance of the participant’s visual estimates was lower than the auditory. The reliability of the visual stimulus for location was manipulated by blurring the image, leading to increased variance in participant estimates. In the dual modality condition, the flash and click were either presented in the same location, or slightly displaced relative to one another (cue-conflict condition). The dual modality variance was well predicted by the MLE model prediction, as derived from the unisensory variance (equation 3). In the cue-conflict condition, participant estimates of the location of the stimuli were closer to the visual cue, suggesting that vision was given greater weight in the multisensory estimate. Where the dual modality stimuli included a blurred visual stimulus, participant’s estimates were biased towards the auditory cue. This suggests that the spatial ventriloquism effect (Slutsky & Recanzone, 2001; Warren, Welch, & McCarthy, 1982), whereby an auditory stimulus is typically mislocated towards a co-occurring flash, may be the result of the optimal integration of audio-visual cues when estimating the location of the stimuli.

Gepshtein and Banks (2003) utilised a visual-haptic height judgement task presented using virtual reality equipment (similar to Ernst & Banks, 2002). Variance in the unisensory visual condition was lower than the haptic condition. When the visual bars
appeared perpendicular to the participant’s line of sight, the variance of the visual estimate increased. Dual modality variance was reduced in comparison to either unisensory condition, and approximated the MLE predictions. In a condition in which the visual-haptic cues were presented in size conflict, participants’ PSEs moved towards the more reliable visual cue. If the visual cue simulated a bar perpendicular to the participant’s line of sight in this dual modality conflict condition, the PSEs moved towards the haptic cue as predicted by the MLE model.

The optimal integration of visual-haptic cues appears to be spatially modulated. Participants completed a size judgement task for virtual reality bars (Gepshtein, Burge, Ernst, & Banks, 2005). When these bars were presented in apparent spatial coincidence, dual modality estimates were well predicted by the MLE model, similar to the previously described studies. However, when the visual-haptic stimuli appeared at a horizontal offset of 60mm or more, performance in the multisensory condition approximated that of the unisensory. A similar task presented a ‘tool’, visually linking the position of the participant’s fingers to the visual bar across a spatial offset (Takahashi, Diedrichsen, & Watt, 2009). If the tool was consistent with natural use (appearing to be manipulated by the front of the participants fingers), performance approximated the predictions of the MLE model. This suggests that the optimal weighting of visual-haptic cues occurs when both stimuli are presented within the representation of peripersonal space (see section 6.1.1) around the hand. This representation can be extended with the active use of tools (Holmes, Calvert, & Spence, 2007; Maravita, Spence, Kennett, & Driver, 2002).

While the studies described so far have explored cue-integration using virtual stimuli, performance approximating the optimal integration of visual-haptic cues has also been replicated using real life stimuli. Helbig and Ernst (2007) presented participants with a 3-D printed cylinder divided by an opaque panel. Participant’s viewed the cylinder on the front of the panel, and explored the cylinder on the back haptically. The task was to determine whether the shape of the cylinder was an ellipse oriented vertically or horizontally. Variance was lower in the unimodal visual condition than the haptic condition, and the variance in the dual modal condition was equivalent to the predictions of the MLE model. The dual modality condition included trials with the shape of the cylinder presented on each side of the panel in conflicting orientations. The participant’s PSE in these conflict conditions was biased towards the visual cue. However, where the reliability of the visual estimate was reduced by viewing the stimuli through a blurring film, the PSEs moved towards the shape of the haptic cue. This
suggests that perception of natural environments is likely to approximate the MLE model and not only performance on virtual tasks.

2.1.3.3. Optimal multisensory cue integration and development
Evidence has been reported that young children do not weight multisensory cues optimally, with the process maturing across development (Gori, Tinelli, Sandini, Cioni, & Burr, 2008). Children aged 5, 6, 8 and 10 years old completed a real life version of the visual-haptic size judgement paradigm developed by Ernst and Banks (2002). Wooden blocks were attached to both sides of an occluding screen; participants viewed the block on the front of the screen and reached behind to explore a block haptically. Cue-conflict was introduced in the multisensory condition as blocks of different heights were fixed to either side of the screen. The performance of adults and children aged 10 years old was well predicted by the MLE model. Children aged 8 years old weighted their estimates according to relative reliabilities, but performance was not well predicted by the model. The estimates of children aged 5 and 6 were counter to the predictions of the MLE model. As with the older participants, variance was lower in the unimodal visual trials than haptic trials. However, performance in the dual modality conflict conditions was biased towards a haptic standard. This suggests that, for younger children, the less reliable haptic estimate was given greater weight in the multisensory judgement (see Figure 2.3). These findings were replicated using an orientation task. Participants were asked to judge whether a standard or comparison block was presented at a greater counter clockwise rotation. All participants produced lower variance for unisensory haptic estimates. The performance of adults and older children was closer to the haptic standard in dual modality judgements, while the younger children showed a bias towards vision. The authors of this paper proposed that cue-integration does not occur in young children as it is more important for the perceptual systems to recalibrate with the growing body.
Figure 2.3 Performance of children aged 5 years and adults on a visual-haptic size discrimination task. In the adult group thresholds (equivalent to SD here) were lower in the dual modality condition than for either unisensory condition. Measured performance was well predicted by the MLE model and PSEs measured in each conflict condition were close to those predicted by the model. Children aged 5 did not show a multisensory performance enhancement as variability was increased in the dual modality condition over either unisensory. The PSEs ran counter to the predictions of the model as children up weighted the more variable haptic information in the cue-conflict conditions (taken from Gori et al, 2008).

2.1.4. Sub-optimal weighting of multisensory cues in ASC as an account of sensory atypicalities.

Since optimal multisensory cue integration appears to follow a developmental trajectory, we hypothesised that atypical neuronal development in ASC may impact on the maturation of this process. For instance, increased neural excitatory activity in sensory systems in ASC (Rubenstein & Merzenich, 2003) may require recalibration beyond early childhood. The perceptual benefits of optimal cue integration (i.e. less variable estimates) may be traded for a more plastic interaction between the sensory modalities in adulthood. There is evidence that children with ASC place a greater reliance on proprioception than NT controls during motor co-ordination tasks (Haswell, Izawa, Dowell, Mostofsky, & Shadmehr, 2009) and the rubber hand illusion (Cascio, Foss-Feig, Burnette, Heacock, & Cosby, 2012). If a less reliable sensory modality is given greater weight in a multisensory estimate, then the percept will be noisier. It is likely that noisy perceptual estimates would result in atypical sensory experiences such as sensory overload (O’Neil and Jones, 1997) as the perception of the environment would be less predictable. Furthermore, sub-optimal weighting of visual and haptic cues may
contribute towards motor abnormalities reported in ASC, particularly when interacting with objects (Gowen & Hamilton, 2013).

In summary, a number of studies have indicated that adults combine spatially coincident visual-haptic cues in a manner which is well predicted by a statistically optimal MLE model. This process appears to mature through childhood development. We reasoned that this maturation may be affected in ASC meaning that adults with ASC would not combine visual-haptic cues in a statistically optimal manner.

2.1.5. Methodological considerations
In Experiment 1, we investigated visual-haptic cue integration in a group of adults with ASC using an adapted version of the visual-haptic size discrimination task (cf. Gori, 2008). This task was developed in a pilot experiment using NT participants (reported in Appendix B1). The procedure of Gori et al (2008) was replicated as closely as possible, however we made a number of adaptations to increase experimental control and reduce testing time. Firstly, the inter stimulus interval was constrained to ensure the effects of working memory decay remained approximately constant in all conditions. In the Gori et al study the inter stimulus interval was not reported and may have varied between conditions and participants. Second, the presentation of the visual stimuli was precisely controlled with occluding spectacles, while participants in the Gori et al study opened and closed their eyes when instructed by the experimenter. Third, in the Gori et al study comparison block sizes increased in 1mm increments, while we used increments of 2mm to reduce testing time.

The statistically optimal weighting of visual and haptic cues for size judgements observed previously (Ernst & Banks, 2002; Gori et al. 2008) were not replicated in the pilot study reported in Appendix B1. Moreover, participants did not exhibit a performance enhancement in the dual modality condition, which is an index of multisensory processing and critical to the MLE model.

In light of these findings, we added two further comparison stimuli with sizes 53mm and 57mm in each condition. This improved the spatial resolution of the psychometric functions around the standard stimulus size (55mm). It was anticipated that this increased resolution would make our experiment more consistent with that of Gori et al. (2008) and therefore improve the likelihood of observing expected differences in performance between the conditions. However, we were still keen to minimise experiment duration with ASC participants. To offset the increase in testing time we,

\[1\] We considered testing time to be a key constraint when working with ASC participants.
removed the non-conflict dual modality condition (see methods below). The formulation of the MLE model does not require this condition to be included as the weights can be extracted from the unisensory condition and compared to performance in the conflict conditions. Furthermore, an assumption of cue-conflict studies is that both cues are automatically combined in an attempt to maintain a non-conflict percept (Welch & Warren, 1980). An average of each participant’s performance in each cue-conflict condition was instead used as an estimate of multisensory performance in the no-conflict condition.

2.1.6. Experiment 1 predictions
It was predicted that NT performance in the dual modality conditions would be consistent with the MLE model, while performance of participants with ASC would differ significantly from the model predictions. It was anticipated this would be reflected in increased variance in the multisensory condition in comparison to the MLE prediction of combined variance and/or departure from the MLE predicted PSE shifts in the conflict conditions for ASC participants.

2.2 Experiment 1 Method

2.2.1 Participants
13 participants with ASC and 13 NT controls matched for age, IQ, gender and handedness took part in Experiment 1. Participants were recruited through adverts in the local community, the Autistic Society Greater Manchester and Tameside Autism Network. Diagnosis was confirmed using module 4 of the Autism Diagnostic Observation Schedule (ADOS; Lord et al., 2000) by a certified assessor. Participants were aged 19-54. Participant characteristics are included in Table 2.1. IQ was measured using the Weschler Adult Intelligence Scale (WASI-IV; Weschler, 1999) in a separate session. Two participants with ASC and two controls were reported as left handed using the Edinburgh Handedness Inventory (EHI, Oldfield, 1971). All participants had normal or corrected to normal vision (6/6 vision in both eyes as measured using Snellens test of visual acuity), and 60s arc stereo acuity as measured using the TNO test. No participant reported a history of a visual condition. To confirm sensory symptoms in our ASC sample all participants completed the Glasgow Sensory Quotient (GSQ; Robertson & Simmons, 2013). The GSQ is a 42 item Likert style questionnaire designed to assess sensory differences in adults with ASC. The GSQ investigates both hyper and hypo functioning across a number of sensory modalities (see Table 2.1). All participants gave written consent and the study was approved by the University of Manchester ethics committee in accordance with the Declaration of Helsinki. In all subsequent experiments
participants completed the visual and handedness tests. All participants with ASC also completed the ADOS.

Table 2.1 Characteristics of participants with ASC and NT, including t-test statistics. Mean ± standard deviation values are presented. Significant difference denoted by asterisk.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>ASC</th>
<th>NT</th>
<th>t(24)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>30.46 ± 10.22</td>
<td>31 ± 11.34</td>
<td>.13</td>
<td>.900</td>
</tr>
<tr>
<td>FSIQ</td>
<td>117.77 ± 10.02</td>
<td>112.61 ± 8.26</td>
<td>1.43</td>
<td>.165</td>
</tr>
<tr>
<td>GSQ score (Bonferroni corrected, α = .016)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total sensory score</td>
<td>64.92 ± 8.36</td>
<td>42.92 ± 24.92</td>
<td>2.10</td>
<td>.046</td>
</tr>
<tr>
<td>Total hyper score</td>
<td>32.62 ± 12.70</td>
<td>20.54 ± 10.06</td>
<td>2.69</td>
<td>.018</td>
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<tr>
<td>Total hypo score</td>
<td>32.03 ± 16.98</td>
<td>18.69 ± 9.40</td>
<td>2.53</td>
<td>.013*</td>
</tr>
</tbody>
</table>

2.2.2 Apparatus
Wooden blocks (the stimuli) were permanently affixed to each side of eight opaque perspex cartridges (220mm x 180mm). The centre of each block was 110mm from the top and 50mm from the closest edge of the cartridge. The wooden blocks had a width of 150mm. Ten of the cartridges held blocks that ranged in height between 48-62mm in 2mm increments plus blocks 53mm and 57mm in height (the comparison stimuli). An eleventh cartridge held identical blocks of 55mm (the standard). Two cartridges had blocks of different heights affixed to the front and back: one cartridge held a block 58mm in height on the front and 52mm in height on the back (referred to herein as conflict 1). The other held a 52mm block on the front and a 58mm block on the back (referred to herein as conflict 2). The average height of the blocks on both of these cartridges was thus 55mm. See Figure 2.4.
Figure 2.4 The cartridges used in each conflict condition, A displays conflict 1 and B displays conflict 2.

The cartridges were inserted into a Perspex screen which remained at approximately 400mm viewing distance from the participant. A laptop running E-Prime (Psychology Software Tools Inc., USA) was controlled by the experimenter and enabled the use of PLATO visual occlusion spectacles (Translucent Technologies Inc., Canada) to control the visual presentation of stimuli. The laptop was also used to generate the stimulus orders, and for the experimenter to record participant’s responses. See Figure 2.5 for the experimental set up.

Figure 2.5 Schematic of the experimental set up. A: a dual modality trial. The participant views the visual stimuli on the front of a removable cartridge while exploring the haptic stimuli on the back of the cartridge using the thumb and forefinger of their dominant hand. B: the inter-stimulus interval. The participant returns their hand to the arm rest and the PLATO glasses were closed while the experimenter changed the cartridge.
2.2.3 Design and procedure
In each trial participants were asked to compare the heights of two blocks, a standard (55mm in height) and a comparison stimulus of variable height (48, 50, 52, 53, 54, 56, 57, 58, 60, 62mm), in a two interval forced choice procedure (2IFC) using the method of constant stimuli.

Trials were presented in three different conditions: visual, haptic and dual modality. In the visual condition, participants viewed the block presented on the front of the screen. To ensure the viewing distance remained consistent between the visual and dual modality conditions (described below) the participant’s dominant arm remained outstretched on an arm rest. At the beginning of each trial the PLATO spectacles remained closed to allow the experimenter to position the first cartridge. Once the first cartridge was in place, the experimenter pressed a button on the laptop which triggered the spectacles to open and begin the trial. The spectacles opened for 1000ms to allow the participant to view the stimuli, and closed during the inter stimulus interval. The second cartridge was positioned and the spectacles opened automatically after 2000ms to allow the participant to view the second stimuli. A sound file of a male voice saying ‘One’ and ‘Two’ played simultaneously with the spectacles opening to remind the participant that they were viewing the first and second stimulus.

In the haptic conditions, participants were instructed to reach behind the screen to feel each stimulus with their thumb and forefinger. The PLATO spectacles remained closed throughout the haptic trials. After positioning the first cartridge, the experimenter pressed a button which began the trial. The participant was instructed to reach towards the stimuli on hearing the same sound file that was used in the visual condition. They were instructed to hold the stimuli for approximately 1000ms before returning their hand to the arm support during the inter stimulus interval. The experimenter positioned the second cartridge and the sound file instructed the participant to reach for the second stimuli after 2000ms.

In the dual modality condition, the visual and haptic conditions were combined so that participants used their sense of vision and touch together. The standard block was always in cue-conflict in the dual modality condition and the comparisons were always cue-consistent. To increase the likelihood of the visual and haptic stimuli being processed simultaneously, the sound file preceded the opening of the PLATO spectacles by 100ms. This allowed participants to begin to reach for the stimuli on the back of the cartridge before the spectacles opened to view the block on the front of the cartridge.
The time profile of the stimulus presentation is represented in Figure 2.6.

![Figure 2.6 Profile of the stimulus presentation in visual, haptic and dual modality trials. The stimulus presentation and inter stimulus interval was kept constant across all conditions.](image)

The inter stimulus interval was constrained at 2000 ms in all trials to allow for the positioning of the second stimulus. Participants responded verbally in all conditions which the experimenter recorded using the laptop. Breaks were included every 44 trials. The average trial length was 15.82 seconds (±2.67).

There were 88 trials in each condition (visual, haptic and dual modality [conflict 1 and conflict 2]) giving a total of 352 trials. In each condition participants were presented with the 48 and 62 mm blocks six times, the 50 and 60 mm blocks eight times, and the 52, 53, 54, 56, 57 and 58 mm ten times. Trials were presented in a random order and the order of presentation (standard or comparison first) was counterbalanced for each comparison size. The visual, haptic and dual modality conditions were blocked and the order of testing was randomised across participants.

At the start of each condition, participants completed a practice procedure of at least five trials for that condition (visual, haptic, dual modality). Participants were presented with the 48mm or 62mm comparison stimuli, and a no-conflict 55mm standard on these trials. In the dual modality condition participants were specifically instructed to imagine that the front and back blocks were a single block passing through the cartridge to increase the likelihood of correspondence between the two stimuli (see Ernst, 2008;
Helbig & Ernst, 2007). The experimental procedure began once task instructions were understood for each condition and participants performed at 80% accuracy.

2.2.4 Analysis
The proportion of trials for which the participant reported the comparison as larger than the standard was calculated for each condition. Individual participant data was fitted using Cumulative Gaussian psychometric functions. Each psychometric function was then characterised by two parameters, μ and σ reflecting the mean and SD of the underlying Gaussian distribution. The first parameter provides a measure of the PSE at which the comparison stimulus was seen as the same size as the standard. The second parameter reflects the discrimination threshold for block size and provides a measure of sensory variability (SD), and thus reliability (see Appendix A for more details).

Analysis of SD data
Data for each participant was compared with the predictions of the MLE model to assess optimal cue-integration. The fitted sensory variance parameters $\sigma_v^2$ and $\sigma_h^2$ were input into equation 3 to derive an MLE prediction $\hat{\sigma}_{vh}^2$. The square root of this value $\hat{\sigma}_{vh}$ was compared to the average of the $\sigma_{vh}$ parameters fitted in the conflict 1 and conflict 2 conditions using a mixed ANOVA. Significant interactions were followed up with t-tests. Data point outliers (NT = 3; ASC = 2) >+ 2SD from the condition mean were replaced with the maximum value +1.

Analysis of PSE data
To calculate a predicted PSE under MLE for each participant the visual and haptic weights (equation 5) were put into equation 6 for each conflict condition. Pearson’s correlation coefficients were calculated for each group to explore any relationships between the PSE measured in the dual modality conflict conditions and the MLE predictions of the PSE.

Visual and haptic weights were also calculated for each participant using the PSE data according to equation 6 (Gori et al, 2008).

$$w_h = \frac{(1-m)}{2}, w_v = 1 - w_h$$ (eq. 6)

$m$ is the slope calculated using a linear regression of that participant’s PSE in each dual modality condition (conflict 1 and conflict 2). The weights extracted from the PSE data were then compared with the weights extracted from the SD data (equation 5) using paired sample t-tests. If the weights extracted from the PSE and SD data are comparable
it suggests that there are no systematic differences between participants measured and predicted performance.

The PSEs measured for each dual modality condition were then compared with the best linear fit for the MLE predictions (equation 4), a prediction of complete visual dominance (visual capture) and a prediction of complete haptic dominance (haptic capture). R was calculated for each model according to equation 8 (Gori et al, 2008).

\[
R = \frac{\sum_{i=1}^{n}(S_i - \bar{S})^2 - \sum_{i=1}^{n}(S_i - \hat{S}_i)^2}{\sum_{i=1}^{n}(S_i - \bar{S})^2} \quad (eq \ 7)
\]

Where \( n \) is total number of PSE values for each participant in each dual modality condition (conflict 1 and conflict 2), \( S_i \) is the PSE for an individual participant, \( \bar{S} \) is the mean of all participants’ PSEs in the dual modality condition and \( \hat{S}_i \) is the predicted PSE for that condition (see Table 2.2). A value of \( R = 1 \) would indicate that the model provided a perfect prediction of the data. \( R = 0 \) would indicate that the model was comparable to the group average while a value of \( R < 0 \) would indicate that the measured PSE fell closer to the group average than the model prediction.

<table>
<thead>
<tr>
<th></th>
<th>Conflict 1 (mm)</th>
<th>Conflict 2 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual capture</td>
<td>+3</td>
<td>-3</td>
</tr>
<tr>
<td>Haptic Capture</td>
<td>-3</td>
<td>+3</td>
</tr>
<tr>
<td>MLE prediction</td>
<td>((w_v \times 3) + (w_h \times -3))</td>
<td>((w_v \times -3) + (w_h \times 3))</td>
</tr>
</tbody>
</table>

### 2.3 Results

A sample Psychometric function is included in Figure 2.7. Mean standard deviation \( \sigma \) parameters are plotted in Figure 2.8. If participants combine the dual modality inputs in a statistically optimal manner then the SD measured in the dual modality condition and the prediction from the MLE model will not differ significantly (see adult data in Figure 2.3). A multisensory performance enhancement for either group would be indicated by a reduced SD in the dual modality condition in comparison to the unisensory conditions.
Figure 2.7 Sample Psychometric functions for a single participant. A: data from the visual unisensory (red plus signs) and haptic unisensory (blue squares) conditions. B: data from conflict 1 (green upward triangles) and conflict 2 (magenta downward triangles). If the curve for conflict 1 shifts rightward and the curve for conflict 2 leftward, it suggests that the participant is up weighting vision. Accordingly when conflict 2 shifts rightward and conflict 1 shifts leftward, it suggests that the participant is up weighting haptics.

2.3.1 Standard Deviation data
A mixed ANOVA (Greenhouse-Geisser adjustment) with group as the between subject factor was conducted to compare the size of the SD between the conditions. A significant effect of condition ($F (2.02, 48.57) = 22.23, p < .001, \eta^2_p = .586$), indicated the size of the SD differed between the conditions. This effect was followed up with paired sample t-tests (Bonferroni corrected, $\alpha = .008$). As mentioned above, there were two critical tests: firstly if participants were combining the unisensory cues a multisensory performance enhancement would be indicated by a reduction in the SD in the dual modality condition in comparison to either unisensory cues. As can be observed in Figure 2.8, the dual modality SD was significantly larger than the visual SD ($t (25) = 4.70, p = .004, d = 0.84$). The dual modality SD was lower than the haptic SD, but this difference did not reach statistical significance ($t (25) = 2.01, p = .056, d = 0.50$). Second, the critical test of optimal integration of these cues would be given by comparable SD between the MLE prediction and performance measured in the dual modality condition. However, the dual modality SD was significantly larger than the MLE prediction of SD ($t (25) = 6.22, p < .001, d = 1.70$). The visual SD was significantly lower than the haptic SD ($t (25) = 4.53, p < .001, d = 1.19$), and as would be expected the MLE prediction of SD was significantly lower than the visual SD ($t (25) = 4.70, p < .001, d = 0.62$) and haptic SD ($t (25) = 7.61, p < .001, d = 1.93$). There was no main effect of group ($F (1, 24) = 1.31, p =$
.23, $\eta_p^2 = .05$) indicating that the size of the SD was similar across the conditions for participants with ASC and NT. Finally, there was no group x condition interaction (F (2.09, 50.15) = .11, $p = .901$, $\eta_p^2 = .005$) indicating that participants with ASC and NT produced similar SD in each condition.

Figure 2.8 Standard Deviation measured in each condition and the prediction from the MLE model. The dual modality data was estimated from an average of the SD in conflict 1 and conflict 2. Error bars denote SEM.

2.3.2. PSE data
Individual PSEs measured in the dual modality conflict conditions, and predictions from the MLE model are displayed in Figure 2.9. Performance consistent with the MLE model would be indicated by a significant positive correlation between measured and predicted PSEs for either group. However, Pearson’s correlation tests revealed that there was no significant relationship for participants with ASC ($r = .201, p = .314$) or NT ($r = .102, p = .628$).
Figure 2.9 Participants with ASC and NT measured PSE for conflict 1 (top; visual block of 58mm and a haptic block of 52mm) and conflict 2 (bottom; visual block of 52mm and haptic block of 58mm) plotted against the prediction for that condition (see equation 4). If the data points fall closely to the solid \( x = y \) line then it suggests that they are performing in a manner well predicted by the MLE model. The dashed line indicates where data points would fall for complete visual capture and the dotted line for complete haptic capture.

The proportion of variance of the PSE data that was explained by visual capture, haptic capture and the MLE model predictions were compared for each group using equation 7. For participants with ASC visual capture, \( R = -1.24 \), for haptic capture, \( R = -6.18 \), and for the MLE model \( R = -0.31 \). For NT participants visual capture, \( R = -1.86 \), for haptic capture, \( R = -3.03 \), and for the MLE model \( R = -0.48 \). Each participant’s performance is displayed as a function of their MLE prediction and a prediction for visual and haptic capture in Figure 2.10.
Figure 2.10 PSEs plotted as a function of cue-conflict in each of the dual modality conditions (conflict 1 and conflict 2) for participants with ASC (A) and NT (B). The dotted black line is the best linear fit of the measured data points for each participant. The solid black line is the MLE prediction for that participant, the red line is the prediction for complete visual dominance and the blue line for complete haptic dominance. Note that the slope of the linear fit of the measured data points (dotted black line) is used to calculate the weights from PSE data according to equation 7.
2.4 Interim discussion

The optimal integration of visual-haptic cues in participants with ASC and NT was investigated in Experiment 1. An MLE prediction of statistically optimal dual modality standard deviation (SD) was calculated from the unisensory data. This value was compared to an estimate of the dual modality SD which was derived as an average of the SD measured in each dual modality conflict condition. The SD predicted by the MLE model was significantly lower than this dual modality SD. Furthermore, participant PSE measured in the dual modality conflict conditions were not significantly correlated with the PSE predicted by the MLE model for either group. For both groups the MLE model provided a better prediction of PSE data than a model of complete visual and complete haptic dominance, but this was no better than the measured mean PSE values for that group (Gori et al., 2008). In Experiment 1, neither participants with ASC nor NT performed in a manner consistent with the statistically optimal MLE model of visual-haptic cue integration.

In Experiment 1, participants with ASC and NT did not show a multisensory performance enhancement. The SD data in the dual modality condition was not reduced in comparison to the unisensory conditions. A performance enhancement is a measure of multisensory processing and is integral to the formulation of the MLE model. We considered two possible accounts for the lack of multisensory performance enhancement which prompted further analysis as detailed below.

2.5 Additional analysis

2.5.1 Within group differences in cue combination

First, we considered that a subset of participants in either group may have produced a multisensory performance enhancement. Eyeballing the data in Figures 2.9 and 2.10 there is some variability between participants in each group in how consistent the participant’s PSEs measured in the conflict conditions were with the PSEs predicted by the MLE model. The NT participants who produced PSE data that was consistent with the MLE model predictions of the PSE may have been combining the visual-haptic cues. It is anticipated that this subgroup would produce a multisensory performance enhancement in the SD data and that there would be no significant difference between the dual modality SD and the MLE prediction. For each participant, a difference score was calculated by subtracting the MLE predictions of the PSE from the measured PSE in the conflict conditions. The groups were split at the median of these difference scores and the SD analysis was then repeated. The full analysis is included in Appendix B2.
The sub-groups did not produce a performance enhancement in the dual modality condition over unimodal performance and the MLE prediction was significantly lower than the SD measured in the dual modality condition (Figure 2.12). This suggests that even participants who produced PSEs that were closer to their MLE predictions were not integrating the information from the visual and haptic cues.

![Graph A](image1.png)

![Graph B](image2.png)

*Figure 2.11 Mean SD measured in each condition and the prediction from the MLE model. A: participants with PSEs that were more consistent with the MLE model (ASC n = 7; NT n = 6). B: participants with PSEs that were less consistent with the MLE model. Error bars denote SEM.*

2.5.2. Cue switching
A second potential account of our data was based on the idea that performance might be better predicted by a stochastic cue-switching model (SCS; Kuschel, Luca, Buss, & Klatzky, 2010; Landy & Kojima, 2001; Nardini, Jones, Bedford, & Braddick, 2008). This model predicts that the participant does not combine the cues when presented in
conditions of conflict, but switches between them. The participant does not switch randomly, but is likely to consider the more reliable cue more frequently (Serwe & Trommershäuser, 2009). The variance predicted by the SCS model is not reduced compared to the unisensory estimates, but tends to be slightly increased as processing both the conflicting cues without combining them may produce perceptual confusion (Kuschel, 2010).

The SCS model predicts that the dual modality variance should be a weighted average based on the unisensory estimates plus a component due to the discrepancy between the cues:

\[ \sigma_{vh}^2 = w_v \sigma_v^2 + w_h \sigma_h^2 + w_v w_h (\mu_v - \mu_h)^2 \]  

(eq.8)

Where the weights relate to the probability of following either cue. The weights are calculated as the perturbation of the participant’s PSE from a given cue in the conflict as a ratio of the overall conflict (see Landy, 1995; Young, 1993). For extracting the visual weight from conflict 1:

\[ w_v = \frac{\text{cue}_1 - \mu_{\text{conflict}_1}}{\Delta \text{cue}} \]  

(eq.9)

Where \( \Delta \text{cue} \) refers to the size of the conflict between the cues (in this instance 6mm) and \( \text{cue}_1 \) refers to the physical properties of the haptic block in the conflict (52mm in conflict 1). \( w_v \) therefore represents the extent to which the participant is following the visual cue when making size estimates in that conflict condition. This is represented in Figure 2.13.
Figure 2.12 Example of the calculation of weights from the perturbation in the dual modality conflict 1 condition. Cue 1 refers to the block on the back of the cartridge (52mm in height for conflict 1) and cue 2 the block on the front (58mm in height). The broken line gives Δ cue and $w_v$ and $w_h$ are given by the distance of the participant’s PSE from the physical height of cue 1 and cue 2.

A previous study of visual and proprioceptive cue-combination indicated that the SCS model provided a better prediction of performance than the MLE model in NT adults (Serwe & Trommershäuser, 2009). Participants made judgements regarding the direction of moving radial lines presented visually and a proprioceptive cue which was presented using a haptic force feedback device. In the dual modality condition, the participant was instructed to focus on the proprioceptive cue while ignoring the visual stimulus. Participant SD data were closer to the predictions of the SCS model than that derived from the optimal MLE model. The SCS model has also previously been shown to be consistent with the performance of children aged 4-8 on a navigation task in which visual cues were presented in conflict to self-motion cues. Adult performance on this task was well predicted by the MLE model (Nardini et al., 2008).

For each participant, an average of the weights calculated from conflict 1 and conflict 2 were inputted into equation 8. The dual modality SD was compared with the prediction derived from the SCS model (see Figure 2.14).

Figure 2.13 Mean SD in each condition, the MLE prediction and the SCS prediction for each group. Error bars give SEM. Significant differences are denoted by asterisk.

Paired sample t-tests (Bonferonni corrected, $\alpha = .025$) were conducted to compare the SD predicted by the SCS model with the SD measured in the dual modality condition.
The SCS prediction was lower than the dual modality SD, but not significantly so for participants with ASC ($t(12) = 1.19, p = .256, d = 0.57$), or for NTs ($t(12) = .20, p = .845, d = 0.13$).

To illustrate individual differences in the data, Figure 2.15 includes each participant’s measured performance and predictions derived from both the MLE and SCS model.

![Figure 2.14](image)

*Figure 2.14 SD measured for each participant including the dual modality condition (star), MLE prediction (solid line) and SCS prediction (broken line).*

2.5.3. Correlations between self-reported sensory traits and psychophysical measures

In an attempt to characterise individual differences in performance, questionnaire data were correlated with the experimental data. Firstly, Pearson’s correlation coefficients (Bonferroni corrected $\alpha = .013$) were calculated to explore the relationship between the SD in the visual and haptic condition and participants total visual and tactile score as measured using the GSQ. There were no significant correlations for participants with ASC ($r < .38, p > .197$) or NT ($r < .23, p > .450$).

Second, measures of each participant’s proximity to the MLE and SCS model predictions were calculated as the difference between their dual modality SD, and MLE and SCS prediction. Pearson’s correlation coefficients (Bonferroni corrected $\alpha = .008$) were calculated to explore any relationships between participants difference scores and self-reported total sensory score, hypo and hyper sensitivity scores. There were no
significant correlations for participants with ASC ($r < .41, p > .162$) or NT ($r < .60, p > .300$).

2.6. Experiment 1 Discussion

2.6.1 Summary
The aim of Experiment 1 was to investigate whether the optimal integration of visual-haptic information observed in NT would extend to participants with ASC. Adult participants with ASC and NT completed a visual-haptic size judgement task with MLE predictions of SD and PSE derived from unisensory data for each participant. Performance in the dual modality condition was not consistent with the MLE model for either ASC or NT participants. Performance was then compared with a non-optimal SCS model. SD data for both groups was indistinguishable from the prediction of the SCS model.

2.6.2 Unisensory performance
The SD in the visual condition was significantly lower than in the haptic condition, which is consistent with previous studies which have investigated visual-haptic height judgements in NT adults (e.g. Ernst & Banks, 2002; Gori et al., 2008). Unisensory performance was comparable between ASC participants and NT controls. Accurate visual judgements in this experiment would require intact contrast sensitivity. The participant is required to detect the height of the matt black wooden block against the grey background of the cartridge. A number of previous studies have indicated that sensitivity to contrast of static stimuli is typical in adults with ASC (see Simmons et al., 2009). There is little experimental research investigating haptic processing in ASC. In a previous study adult participants with ASC and NT were asked to identify shapes that they had previously been shown visually, using only haptics (Nakano, Kato, & Kitazawa, 2012). For more complex shapes the participants with ASC performed more accurately than controls, suggesting that haptic processing is superior to NTs. In the current study, more simple size discrimination using only haptic information appears to be typical in participants with ASC.

2.6.3 Multisensory performance and comparisons with the MLE model
In Experiment 1 multisensory performance enhancements were not observed for either group. The SD in the unisensory visual condition was significantly lower than the dual modality condition. A number of studies have suggested that individuals with ASC do not produce a performance enhancement on audio-visual tasks (Brandwein et al., 2013; Collignon et al., 2013). However, this finding was unexpected in NT participants and a number of possible methodological factors are discussed below. A multisensory
performance enhancement is critical to the MLE model, each sense is combined so that
the multisensory estimate is more reliable than either of the unisensory estimates.
Accordingly, both ASC and NT performance was not well predicted by the model.
Furthermore, a regression analysis revealed that the PSE data was not well predicted by
the MLE model for either group. Although a large body of research has indicated that
performance on multisensory tasks is well predicted by the MLE model, there are
studies which have failed to replicate the optimal integration of multisensory cues in NT
adults. Adults and children aged 6 years old completed a visual-haptic task in which they
judged the lengths of physical stimuli (Jovanovic & Drewing, 2014). This study presented
participants with a visual, haptic or dual modality standard in comparison to unisensory
haptic stimuli. Conflict was introduced in the dual modality condition by magnifying the
visual stimuli. Both adults and children’s performance in the combined condition was
significantly larger than the predictions of the MLE, but smaller than the SCS prediction.
Haptic alone performance was as good, or better, than performance in the combined
condition in adults indicating no multisensory performance enhancement. However, this
task required potentially effortful visual-haptic matching in the dual modality condition
which may eliminate the benefit of processing multiple cues. A virtual study of visual-
haptic softness perception indicated that adult performance was not well predicted by
the MLE model (Cellini, Kaim, & Drewing, 2013). Unisensory haptic judgements were
less variable than visual. Participants produced a greater weighting of vision in the
combined estimate than predicted, and performance deviated from the predictions of
the MLE model. Moreover, where the stimuli were perceived as hard, haptic
judgements were more reliable than multisensory judgements. It may be that in certain
experimental settings introducing a second modality, when a single modality is much
more reliable, may simply cause confusion leading to a performance detriment. Indeed,
the predicted improvement in performance is largest when the variance associated with
each cue is approximately equal (Landy et al., 1995). In the present study, the SD in the
visual condition was much lower than the haptic. If participants were not combining the
cues in the multisensory conditions, the presence of the less reliable haptic stimuli may
have caused confusion, leading to more variable estimates than vision alone (Kuschel et
al., 2010).

We considered that a sub- group of participants may have been combining the cues
appropriately and that these participants would be more likely to perform in a manner
consistent with the model. A median split was used to divide the groups according to
the difference between the measured and predicted PSEs. However, the pattern of
results was the same. The SD was increased in the dual modality condition in comparison to both the unisensory visual condition and the MLE predictions.

Finally, performance in the dual modality condition was compared with the predictions of an alternative, non-optimal model. The SD predicted by this SCS model did not differ statistically from performance measured in the dual modality condition. This is in line with a previous study which investigated the combination of visual and proprioceptive cues (Serwe & Trommershäsuer, 2009). There are a number of methodological factors which may have contributed to the participants adopting this strategy.

2.6.4 Methodological factors
In the present study, the discrepancy between the cues in the conflict condition was relatively large (6mm) and the visual-haptic stimuli were presented with some spatial disparity (the width of the cartridge, 15mm). It has previously been observed that visual-haptic cue integration is progressively reduced with increased spatial disparity between the cues (Gepshtein, Burge, Ernst, & Banks, 2005). The issue of spatial discrepancy between the stimuli and the size of the conflict also applies to the Gori et al study. It has been noted elsewhere that the younger children in this study may have been adopting a cue-switching strategy (Nardini et al., 2008). However, the adult participants and the children aged 10 years old performance approximated the MLE predictions, which was not captured in the present study. Although participants in the present study were not specifically asked if they noticed the conflict a number commented on it, which differs from reports in previous studies using the same paradigm (Ernst & Banks, 2002; Gori et al., 2008). It has previously been suggested that noticing crossmodal conflict should not prevent the cues being combined (Welch & Warren, 1980). However, it may be that the participants perceived a lack of correspondence between the cues (Helbig & Ernst, 2007). Where visual-haptic stimuli are presented with a large conflict they are less likely to be combined (Hillis, Ernst, Banks, & Landy, 2002). Furthermore, cues presented to either modality should only be combined if the participant believes they originate from a common cause, in keeping with the perception of natural environments (Körding et al., 2007). It is possible that the distance between the cues, the screen creating a separation between the visual-haptic stimuli and the size of disparity in the cue-conflict condition together may have caused the participants to notice the conflict. This may have made it less likely that the participant perceived the cues as originating from a single source, preventing the cues from being combined. Where a conflict is noticed, it is likely that the participant will have to adopt a conscious decision making strategy when making judgements about the conflicting stimuli (De Gelder & Bertelson, 2003). In fact,
the integration of cues between the senses is not necessarily mandatory as there are situations in which combing the cues would be inappropriate, for instance, when looking at one object while holding another.

2.6.5. Typical multisensory cue processing in adults with ASC

The aim of this study was to investigate optimal cue integration in participants with ASC. However, we failed to replicate optimal cue integration in our NT control group, but found that participant’s performance was well predicted by a non-optimal cue-switching model. Participants with ASC performed in a typical manner on this task as performance in each condition was statistically comparable to controls. A recent study has explicitly investigated multisensory cue-integration in adolescents and young adults with ASC (Zaidel, Goin-Kochel, & Angelaki, 2015). Participants were required to indicate apparent self-motion using unisensory visual and vestibular, and dual modality stimuli. The visual stimuli were random dot displays and the participant stood on a moving platform which generated vestibular stimuli. For both groups variability was reduced in the visual condition over the vestibular. Performance in the visual condition was comparable between the groups, contradicting previous research which has suggested a deficit for processing visual motion in ASC (e.g. Milne et al., 2002; Spencer et al., 2000). In both groups, dual modality performance was similar to the visual condition, as predicted by the MLE model. When the reliability of the visual stimuli was manipulated by increasing the percentage of randomly moving dots, the variability in performance increased. This detriment in performance was particularly marked in the participants with ASC. When the dual modality condition included visual stimuli with increased noise, both groups up-weighted vestibular information as predicted by the MLE model. This suggests that participants with ASC are more affected by visual noise than NT, but show optimal multisensory cue-integration. This is somewhat in agreement with the present experiment as participants with ASC performed similarly on a multisensory cue-integration task to NT controls. However, it is difficult to make inferences about sensory processing in ASC from the current study as the methodological considerations discussed above may have prevented optimal cue integration being captured in our NT participants.

2.6.6. Conclusions

In Experiment 1, we investigated the combination of visual- haptic cues in participants with ASC using a size judgement task (Ernst & Banks, 2002; Gori et al., 2008). Performance was indistinguishable between participants with ASC and NT controls. For both groups, multisensory performance was not well predicted by a statistically optimal
MLE model (Ernst & Banks, 2002; Landy et al., 1995), but approximated a non-optimal SCS model (Landy & Kojima, 2001; Nardini et al., 2008). Adults with ASC appear to perform typically on this version of the task, but there are a number of methodological factors which may account for the failure to capture optimal cue integration in our NT control group. As there was no dual modality cue-consistent condition, it is possible that the participants may have adapted to the conflict more readily and adopted a cue-switching strategy.

This experiment investigated the interaction between stimuli presented near coincidentally, in the following experiments the limits of multisensory interactions across space and time will be investigated in participants with ASC and NT.
Chapter 3

Adapting the crossmodal congruency task for measuring the limits of visual-tactile interactions within and between groups

Parts of this chapter have previously been published as:


and presented at the following conference presentations:

Applied Vision Association, Manchester meeting (2013)
Multisensory Research Meeting, Birmingham (2012)
Temporal Processing in Clinical Populations, Thessaloniki, Greece (2012)
“Unless we apply the concepts of space and time to the impressions we receive, the world is unintelligible, just a kaleidoscopic jumble of colors and patterns and noises and smells and pain and tastes without meaning.”

Pirsig (1974; Zen and the Art of Motor Cycle Maintenance, pg 121).

3.1 Introduction

In Chapter 3 an existing visual-tactile paradigm, the crossmodal congruency task (CCT; Spence, Pavani, & Driver, 1998) was adapted and developed to measure the interaction between vision and touch in heterogeneous groups. The CCT is a commonly used paradigm for measuring visual-tactile interactions and how these may be influenced by discrepancies in space and time between the tactile target and visual distractors. The majority of studies which have used this paradigm have neither measured, nor attempted to control, individual variability in unisensory (tactile) performance. We developed a version of the CCT in which unisensory baseline performance is constrained to enable comparisons within and between participant groups. This chapter begins with a review of studies which have utilised the CCT, including implications for its use in heterogeneous groups such as ASC. The adapted version of the task was then tested in groups of NT participants in Experiments 2 and 3.

3.1.1 Multisensory processing in heterogeneous groups

There is growing interest in how multisensory interactions may differ in a number of participant groups that report atypical sensory processing. Research has investigated multisensory interactions across typical development and ageing (Hillock-Dunn & Wallace, 2012; Poliakoff, Ashworth, Lowe, & Spence, 2006), and in neurodevelopmental disorders such as dyslexia (Facoetti et al., 2010; Harrar et al., 2014), ASC (Foss-Feig et al., 2010), schizophrenia (Stekelenburg, Maes, Van Gool, Sitskoorn, & Vroomen, 2013), and developmental dyspraxia (Bair, Kiemel, Jeka, & Clark, 2012). Few researchers investigating multisensory processing, however, have attempted to constrain unisensory performance. That is, equating performance between participants in a single sensory modality before measuring the effect of adding an additional modality. When unisensory performance is not controlled, apparent group differences in multisensory processing could arise as the unisensory aspect of a task may vary in difficulty between participant groups, which might produce floor or ceiling effects. Conversely, differences in multisensory processing between-groups could be masked by this variability in unisensory performance. Thus, attempting to constrain and measure unisensory performance is particularly important when investigating multisensory interactions in heterogeneous populations. Controlling unisensory performance by presenting stimuli at the participant’s threshold level has been successfully utilised in studies of audio-
visual interactions in developmental disorders. These studies have revealed that both adults with dyslexia (Hairston, Burdette, Flowers, Wood, & Wallace, 2005) and children with ASC (Kwakye, Foss-Feig, Cascio, Stone, & Wallace, 2011) show effects of task-irrelevant auditory information on visual judgements over longer time intervals. That is, they did not show typical temporal modulation. Presenting stimuli at each participant’s threshold level produced equivalent unisensory accuracy rates between the groups and was particularly important in the Hairston et al. (2005) study, as the participants with dyslexia performed more poorly in the unisensory visual condition. In the present study we have adapted an established visual-tactile task, so that tactile performance can be constrained, providing a measure of the effects of task-irrelevant visual distractors on tactile performance. It was anticipated that the modifications to the CCT described below would improve the suitability of the task for measuring the spatial and temporal modulation of visual-tactile interactions in heterogeneous populations, such as ASC.

3.1.2 The crossmodal congruency task
The crossmodal congruency task (CCT; Spence et al., 1998) is a test of interactions between touch and vision. The task typically involves participants making speeded judgements of the elevation of tactile vibrations presented to the index finger (top) and thumb (bottom) of either hand, whilst ignoring concurrent visual flashes presented by the finger or thumb (see Figure 3.1 for a schematic of the experimental set up). The visual and tactile stimuli are presented at the same (congruent), or different (incongruent) elevations. Typically, participants perform more rapidly and accurately in the congruent condition, and produce more errors and longer reaction times (RTs) in the incongruent condition. The congruency effect (CE) is calculated by subtracting mean error rates and RTs of congruent from incongruent conditions.
Figure 3.1 Schematic of the crossmodal congruency task (image from Spence, Pavani, Maravita & Holmes, 2004). The participant holds a foam cube in each hand in which two tactors and distractors are embedded. The participant is required to make speeded judgements regarding the elevation of the tactile target presented to either hand, while ignoring the visual distractors.

It has been found that CEs are temporally and spatially modulated. Distractors are typically presented 30ms prior to the target stimulus (-30ms) in studies of the CCT as this produces the greatest CE (see Spence et al, 2004). When distractors were presented 50ms, 100ms, 200ms or 400ms before or after the target, it was found that performance became comparable to ‘baseline’ (estimated by averaging performance across all conditions earlier than -200ms) when distractors were presented more than 100ms prior to, or following, the target (Shore, Barnes, & Spence, 2006). That is, multisensory interactions are more likely when stimuli appear at approximately the same time. The -30ms stimulus onset asynchrony (SOA) is believed to produce the greatest CE as the perception of simultaneity is created due to vision having a slower transduction rate than touch (Hsiao, 1998). When the spatial location of the visual distractors is manipulated, it is consistently reported that distractors presented close to the participant’s stimulated hand produce a greater CE than if they are presented near the opposite hand (see Maravita, Spence, & Driver, 2003). That is, visual information which occurs within the participant’s peripersonal space surrounding the stimulated hand is more likely to interact with the concurrent tactile stimulation. The temporal and spatial modulation of CEs is represented in Figure 3.2.
3.1.3 Methodological considerations

In the current investigation, we address a number of potential methodological issues with the CCT to make it more suitable for investigating between group differences which may be particularly useful when exploring visual-tactile interactions in ASC. First, variability in unimodal tactile performance may create difficulties in measuring multisensory effects. As discussed above, if the participant reaches ceiling or floor performance in a single sensory modality, introducing crossmodal stimuli may have little or no effect. To address this issue, we attempted to equate unisensory performance using a threshold procedure prior to the main task. This made it possible to find the stimulus level at which each participant performed the tactile task with an accuracy of approximately 75% (±15%). By presenting the experimental stimuli at approximate threshold level it was anticipated that the increase in task difficulty would allow multisensory interactions to be reliably measured through error rate alone. Indeed, it can be advantageous to analyse error data when investigating groups that may produce variable RT data, such as children, older participants, or in clinical groups such as ASC. It is possible that between-group differences in visual-tactile interactions could be masked by variable within group data. Second, we incorporated a unimodal (tactile) baseline
condition (see also, Poliakoff et al., 2006) with no visual distractors so that performance in unisensory and crossmodal conditions could be directly compared. This provides a useful measure of visual-tactile interactions relative to unisensory processing. Specifically, this makes it possible to determine whether congruency effects are driven by significant facilitation from congruent distractors and/or significant interference from incongruent visual distractors (see Galpin, Tipper, Dick, & Poliakoff, 2011 for a similar approach in investigating facilitation and inhibition in visuomotor processes). Finally, we used a simplified unimanual, single versus double task. The tactile target was presented unimanually to the dominant hand (Spence, Kingstone, Shore, & Gazzaniga, 2001), rather than bimanually as in traditional versions of the task, and participants made a non-spatial (single versus double) tactile judgement (Holmes et al, 2006; Holmes et al, 2008) rather than an elevation judgement, which required only a single Light Emitting Diode (LED). These simplifications were designed to reduce task demands for participant groups (such as ASC) and, as will be described below, to enable spatial modulation to be measured more effectively. The aim of the current study was to replicate the typical temporal and spatial modulation of the CE using this refined paradigm.

2.1.4 Experiment 2 and 3 aims and predictions
The temporal modulation of the CE was investigated in Experiment 2 by manipulating the temporal discrepancy between the target vibration and distractor light (Shore et al., 2006), while always presenting the distractor at a single spatial location next to the stimulated hand. It was predicted that distractors presented 30ms prior to the target would produce the greatest CE.

Experiment 3 was designed to replicate the spatial modulation of the CE (e.g. Holmes et al., 2006; Pavani, Spence & Driver, 2000). Distractors were presented by the participant’s stimulated hand and at an equivalent position in the contralateral hemispace. It was predicted that distractors presented by the stimulated hand would produce a significantly greater CE than the distractor in the contralateral hemispace. Using a unimanual presentation meant that unlike the traditional version of the task, the ‘far’ distractor was not presented next to the opposite (unstimulated) hand. This allowed us to directly explore the effect of increasing distance between the stimulated hand and the visual distractor, without involving the peripersonal space of the opposite hand. Using a single LED, as opposed to the two required for the elevation judgement CCT, also enabled further exploratory analysis of the spatial limits of the CE, since distractors could be presented in a number of locations. Previous studies have investigated this spatial effect by including visual distractors at a position 50cm from the
body midline (Spence & Walton, 2005), at a perceived depth of 150cm as a reflection on a mirror (Maravita, Spence, Sergent, & Driver, 2002), or by horizontally offsetting the position of the stimulated hand away from the visual distractors in the same hemispace (Spence, Kingstone, Shore, & Gazzaniga, 2001). In the present study, additional distractors were placed 21cm and 42cm from the participant’s stimulated hand within the same hemispace, whilst controlling for depth. We predicted that multisensory effects might be observed when visual-tactile stimuli are discrepant by 21cm, as the visual stimuli may fall within the participant’s peripersonal space (Lloyd, 2007), while the distractor 42cm from the hand in the same hemispace would produce no significant CE. In this instance, the spatial modulation of the CE may be dependent on absolute distance from the participant’s hand rather than being positioned in the contralateral hemispace.

An additional aim was to explore the suitability of this adapted task for measuring visual-tactile processing within and between participant groups. First, it was anticipated that presenting stimuli at the participant’s tactile threshold would equate task difficulty between participants, removing any relationship between unisensory acuity and multisensory performance (e.g. those with reduced tactile acuity being more influenced by the addition of visual distractors). To test this prediction, the relationship between tactile threshold and the size of the CE to stimuli presented close to the target in time and space was also investigated. Second, to explore the suitability of the task for investigating visual-tactile interactions in ASC, participants completed the Autism Spectrum Quotient (AQ; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001). The AQ is a questionnaire used to measure autistic traits in non-clinical populations. If individuals reporting more autistic traits produced higher (or lower) tactile thresholds this would suggest that constraining tactile performance should be considered when measuring visual-tactile interactions in clinical ASC.

3.2 Method

3.2.1 Participants
Participants were recruited from the student population and staff at the University of Manchester, and were compensated with £5 for each experiment. The intended sample size for both Experiments was 14, based on a power calculation from pilot work ($d = 0.78$). 14 participants completed Experiment 2 (mean age = 25.07 years ± 4.89; 6 male). Two participants were left handed as self-reported using the Edinburgh Handedness Inventory (EHI; Oldfield, 1971). 13 participants completed Experiment 3 (mean age = 24.54 years ± 4.12; 7 males), including seven of whom had also participated in
Experiment 2. One participant was excluded prior to analysis due to reporting fatigue and appearing to respond at random. One participant was left handed as measured by the EHI.

3.2.2 Apparatus
Participants sat at a desk in a dimly lit room and were instructed to focus on a central fixation point, consisting of a white cross (19 mm) on a computer monitor, displayed approximately 30° below eye level and approximately 45 cm from the participant. A mirror was angled above the participant that allowed the experimenter to ensure that central fixation was maintained.

A bone conductor (Oticon Limited, B/C 2-PIN, 100Ω, Hamilton, UK) was embedded within a 70 mm foam cube. Participants held the cube between the thumb and forefinger of their dominant hand. The participant’s index finger was attached to the bone conductor using double-sided adhesive tape. The bone conductor was driven by sound files (white noise, ~66dB SPL) from a PC through a Tacamp amplifier (Dancer Design, St. Helens UK) to create the tactile vibration. Six 10mm red LEDs, were affixed in symmetrical locations around the monitor. The LEDs were visible through 10mm holes in a black cardboard shield which surrounded the monitor. Each light was 29cm from the fixation cross: one light positioned above the bone conductor, one light 21cm above the conductor offset at an angle of 10°, and one light 42cm directly above the bone conductor. Three lights were fixed in symmetrical positions on the opposite side of the monitor, allowing identical positioning for left handed participants (Figure 3.3).

White noise was played through headphones throughout the experiment to prevent the participant from hearing sounds emitted by the bone conductor (~75dB SPL). The participant’s foot rested with their heel and toe each depressing a foot pedal, throughout the experiment. Responses were recorded by them lifting their heel or toe.

Participants completed the AQ (Baron-Cohen et al., 2001). The AQ is a 50 item Likert questionnaire designed to measure autistic traits in non-clinical populations. Participants are asked to rate items related to everyday experiences, for instance, ‘I prefer to do things the same way over and over’. Higher scores indicate more autistic traits, with scores over 32 believed to indicate clinical significance.
Figure 3.3 Schematic of the experimental set-up including the position of each LED for a right handed participant. The positions of the LEDs were equivalent for left handed participants. Participants were instructed to keep their non-dominant hand underneath the desk throughout the testing session. The photograph displays the bone conductor, foam cube and the LED distractor in the 0cm position.

3.3.3 Procedure

Threshold procedure
Participants received two successive tactile stimuli in a two interval forced choice procedure; a constant (single) vibration and two separate (double) 80ms vibrations separated by a 0-200ms gap. There was a pause of 500ms after the presentation of the first vibration and the order (single or double vibration first) was randomised. The overall duration of the single and double stimuli were matched. Participants fixated the central point on the screen and viewed the words ‘Toe’ or ‘Heel’ that appeared simultaneously with the onset of the first and second vibration respectively. The participant was then instructed via an onscreen prompt to indicate which interval contained the double vibration; lifting their toe from the foot pedal if the double vibration occurred first, or lifting their heel if the double vibration occurred second. The next trial commenced after the participant had made a response (see Figure 3.4 for a diagram of a trial).

An adaptive staircase procedure (PEST; for details refer to Taylor & Creelman, 1967) was used, designed to hone in on a particular target performance level. This method was chosen for the speed with which an approximate threshold may be determined.
Participants received successive trials in which the period of no stimulation (the duration of the gap) between the double vibrations varied. Their performance relative to the target performance level (75% accuracy) at the current gap determined whether the duration continued to increase, decrease or reverse in direction on subsequent trials. Participants began at the maximum gap size of 200ms and the initial step size corresponded to a 16ms reduction in the gap duration. The procedure came to an end when the participant reached the minimum step size, which corresponded to ±1ms in gap duration. After reaching the minimum step size, 20 further trials were included over which the average of the reversals was taken as the threshold value and their accuracy was checked to confirm that the threshold procedure had constrained their performance (i.e. 75% ± 10).

Breaks were included after 90 and 180 trials. To ensure that the threshold procedure was not unduly long, if the participant had not reached the minimum step size by 180 trials, the program ended and an average of the participant’s reversals since the 90th trial was taken. The procedure continued using this average level at the minimum step size of 1ms for 20 further trials (Experiment 2, n = 2; Experiment 3, n = 1). Their threshold was taken as the average gap detected on these trials.

**Experimental Procedure**

Participants were asked to make speeded responses upon the presentation of a target vibration, responding by lifting their toe in response to single pulses, and heel in response to double. Pilot work indicated that this stimulus-response mapping was most intuitive. Throughout the experimental procedure, vibrations were presented at the previously determined threshold level for that participant. The task included both baseline trials and trials with task irrelevant distracting LED light flashes, which were either congruent (e.g. single vibration, single light flash) or incongruent (e.g. single vibration, double light flash). Participants were explicitly instructed to ignore the light flashes as much as possible. A central fixation cross remained onscreen throughout the session. In each trial, a larger, silver version of the cross (24mm) appeared for 750ms to warn participants that the trial was about to commence. The white cross then reappeared 750ms before the onset of the target stimulus and remained onscreen while the stimulus was delivered. Distracting light flashes were presented close in time to the target (see below). For single flashes the LED was illuminated for 80ms, while double flashes comprised two single 80ms flashes separated by 120ms. If the participant responded before the presentation of the vibration, the trial was discounted and the
error message ‘Too early’ was presented for 1000ms. There was an inter-trial interval of 1500ms following the participant’s response (see Figure 3.4. for a schematic of a trial).

![Diagram of a trial](image)

*Figure 3.4 Diagramatic representation of a trial in the threshold and the experimental procedure.*

There were three practice blocks to familiarise participants with the task and ensure that the threshold procedure had worked effectively. They first completed 5 trials with the gap duration set at 200ms to ensure that they understood the task instructions. Participants were then presented with 10 unimodal trials at their threshold level. Finally, the third block comprised 36 trials: 20 unimodal baseline trials and 16 trials with light flashes, four in each condition with each combination of congruent/ incongruent trials with single/double pulses. Participants were required to perform at 75% accuracy ±10% in baseline trials on the third block to continue to the experimental task proper where each error represented a 5% reduction in performance accuracy. Participants who performed at 60% or 90% accuracy had the gap duration increased or decreased by 1ms and were required to repeat the practice procedure (Experiment 2, n = 2; Experiment 3, n = 3). Participants who performed outside of these parameters completed a shortened version of the threshold procedure in which they were re-entered at the final step size reached (Experiment 2, n = 4; Experiment 3, n = 3).

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2 The initial step size was equivalent to ±8ms on the shortened version of the threshold procedure.
The experimental trials followed the same procedure with distractor and baseline unimodal trials intermixed. In Experiment 2, the distractor lights were always presented by the participant’s stimulated hand. There were 9 conditions: distractors (congruent, incongruent) × SOA (-30ms, 100ms, 200ms and 400ms), plus baseline. In Experiment 3, the distractor lights were always presented at -30ms SOA. There were 9 conditions: distractors (congruent, incongruent) × position (0cm, 21cm, 42cm and 42cm on the opposite side, referred to herein as 42cm_opp) plus baseline trials. Both experiments consisted of four experimental blocks of 90 trials, in which each condition was presented 10 times in a randomised order, with half of these trials being single vibrations and half double. This gave a total of 360 trials, with 40 trials in each condition. An enforced break was included after each block and each experiment was completed in a single one hour session.

3.3.4 Data analysis
RTs longer than 2000ms (Experiment 2, 5% of all trials; Experiment 3, 3.1%) and under 150ms (Experiment 2, 0.66%; Experiment 3, 0.40%) were removed from analysis. These errors were likely caused by lapses in attention, anticipation of the target or foot pedal errors and were not included in the error rate. Error rate and RT were calculated for each condition. Participants’ error rates were analysed (Figure 3.5), but RT data is also included in Appendix C1. Within-participant confidence intervals were calculated as outlined by Loftus and Masson (1994).

A 2 x 4 (Congruency x Condition) within participant ANOVA was used to compare error rates across conditions. To determine the influence of task irrelevant visual distractors on unisensory performance, congruent and incongruent conditions were compared with Baseline using paired t-tests (see Figure 3.5). Pearson’s correlation coefficients were calculated to explore any relationships between unisensory tactile threshold and the size of the CE (error rate in the incongruent condition – the congruent condition) for distractors presented at -30ms (Experiment 2) and 0cm (Experiment 3). Pearson’s correlation coefficients were calculated to investigate the relationship between AQ data and unisensory thresholds measured in each experiment. A single threshold value from Experiment 2 was a data point outlier >+2SD from the mean and was replaced with the maximum value + 1%.
3.5 Results

3.5.1 Tactile threshold
Participants produced an average tactile threshold of 27.07ms (±11.12) and 26.78ms (±10.46) gap duration on Experiments 2 and 3 respectively.

3.5.2 Experiment 2
Congruency effects (the difference in error rate between incongruent and congruent trials) were largest in the -30ms condition compared with all later SOA (see Figure 3.5a). A 2 x 4 ANOVA (Congruency x SOA) revealed a significant main effect of congruency, with a large effect, with more accurate responses when vibrations and distractors were congruent rather than incongruent (F (1,13) = 5.89, p = .031 η² = .31). There was no main effect of SOA (F (3, 39) = 2.09, p = .117 η² = .14), but critically, there was a significant interaction between congruency and SOA with a large effect (F (3, 39) = 6.88, p = .001, η² = .35) indicating that the CE varied across SOAs (Figure 3.5a). Firstly, paired t-tests revealed a significant congruency effect for the -30ms condition only (see Table 3.1). Paired sample t-tests were then conducted to compare the congruency effect between each SOA (Bonferroni corrected; α = .008). The congruency effect was significantly greater when distractors were presented at -30ms than 100ms with a moderate to large effect (t (13) = 3.24, p = .006, d = 0.63) and 200ms SOA with a large effect (t (13) = 5.06, p <.001, d = 1.58). No other comparisons between the SOAs reached statistical significance (t <2.96, p >.011).

3.5.3 Experiment 3
Congruency effects were largest in the 0cm condition in comparison to the distant positions (Figure 3.5b). A 2 x 4 ANOVA (Congruency x Position) revealed a significant main effect of congruency with a large effect (F (1, 12) = 8.99, p = .011, η² = .43) and a significant effect of position with a moderate effect (F (3, 36) = 3.74, p = .019, η² = .24). Critically, there was a significant interaction between congruency and position with a moderate effect (F (3, 36) = 3.94, p = .016, η² = .25), indicating that the effect of congruency varied across spatial positions (Figure 3.5b). Firstly, there was a significant CE only for the 0cm position (See Table 3.1). Paired sample t-tests (Bonferroni corrected; α = .008) were then used to compare the CE between each position. Distractors presented at 0cm produced a significantly larger CE than the 42cm_op position with a large effect (t (12) = 3.37, p = .006, d = 0.80) and tended to produce a larger CE than at the 42cm position with a moderate effect (approaching statistical significance; t (12) = 3.12, p = .009, d = 0.78). All other positions were compared, with no differences reaching statistical significance (t < 2.35, p > .037).
Figure 3.5 Mean percentage error at each SOA (Experiment 2; A) and position (Experiment 3; B). Congruent (dark grey bars), Incongruent (light grey) and Baseline (black) conditions. * denotes Bonferroni corrected comparison significant at $\alpha = .013$ (CE, see Table 3.1), and ** significant at $\alpha = .006$ (Baseline comparisons). Error bars represent within-participants confidence intervals (Loftus and Masson, 1994).
Table 3.1 T-test statistics (Bonferroni corrected, \( \alpha = .013 \)) for comparisons of error rate between congruent and incongruent trials at each SOA (Experiment 2), and position (Experiment 3). Asterisks denote significant differences.

<table>
<thead>
<tr>
<th>SOA</th>
<th>t (13)</th>
<th>p</th>
<th>d</th>
<th>Position</th>
<th>t (12)</th>
<th>p</th>
<th>d</th>
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<tbody>
<tr>
<td>-30ms</td>
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<td>0cm</td>
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<td>200ms</td>
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<td>42cm</td>
<td>1.29</td>
<td>.220</td>
<td>0.43</td>
</tr>
<tr>
<td>400ms</td>
<td>.92</td>
<td>.373</td>
<td>0.28</td>
<td>42cm_opp</td>
<td>2.16</td>
<td>.052</td>
<td>0.57</td>
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</tbody>
</table>

Table 3.2 T-test statistics (Bonferroni corrected \( \alpha = .006 \)) for comparisons of error rate at each SOA (Experiment 2) and position (Experiment 3) with Baseline. Asterisk denote significant differences.

<table>
<thead>
<tr>
<th>SOA</th>
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<th>p</th>
<th>d</th>
<th>Position</th>
<th>t (12)</th>
<th>p</th>
<th>d</th>
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<td>0.56</td>
<td>42cm_opp</td>
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<td>.747</td>
<td>0.06</td>
</tr>
<tr>
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<td>.143</td>
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<td>.041</td>
<td>0.59</td>
</tr>
</tbody>
</table>

3.5.4 Correlations with tactile thresholds

**Congruency effect**

The relationship between the CE and participant thresholds was explored to investigate whether distractor processing was related to tactile temporal acuity. There were no significant correlations (Bonferroni corrected \( \alpha = .025 \)) between tactile threshold and the size of the CE for distractors presented at -30ms in Experiment 2 \( (r = .341, p = .233) \), or between the tactile threshold and the size of the CE for distractors presented in the 0cm position in Experiment 3 \( (r = -.104, p = .734) \). See Figure 3.6.
Figure 3.6 The congruency effect (CE) measured for distractors presented at the -30ms SOA (Experiment 2; A) and 0cm position (Experiment 3; B) as a function of unisensory tactile temporal separation thresholds measured in each experiment. Note that these conditions are essentially the same (i.e. the light is presented at -30ms in the 0cm position), although embedded in two different experiments.

**Autistic traits**
Participants had an average AQ rating of 15.69 (± 6.09) and 13 (± 5.05) on Experiments 2 and 3 respectively (see Figure 3.7). The relationship between autistic traits and tactile temporal acuity was investigated. There was no significant correlation between AQ scores and tactile threshold (Bonferroni corrected α =.025) in Experiment 2 (r = .48, p = .082), while there was a statistically significant moderate to strong positive correlation between AQ scores and tactile threshold in Experiment 3 (r = .646, p = .017). See Figure 3.7.
3.6 Discussion

In the current investigation, we attempted to measure the temporal and spatial modulation of visual-tactile interactions using a modified version of the crossmodal congruency task (CCT) in which individual unisensory performance was constrained to 75% (±15%) accuracy. In Experiments 3 and 4, we revealed a congruency effect (CE) whereby task irrelevant lights influenced the errors made in judgements about vibrations. In Experiment 3 the CE was greater when lights were presented 30ms before the target than when presented later in time. In Experiment 4 the CE was greatest when lights were presented next to the target in comparison to positions further away. There were no significant CEs at any other position or SOA, replicating previous findings using the CCT (e.g. Shore et al., 2006; Spence et al., 1998). The present experiments have captured temporal and spatial modulation of visual-tactile interactions using this modified version of the CCT.

As previously reported by Holmes et al. (2006), the effects obtained using the traditional elevation judgement CCT can be replicated using a version of the task in which participants judged whether a vibration was single or double. Unisensory tactile (baseline) performance was also measured in the current study and compared to conditions including visual distractors. Comparing performance in this way enables the facilitatory and interference effects of visual distractors on tactile performance to be disentangled. A significant interference effect when incongruent distractors were presented at 0cm was observed in Experiment 3. Separating facilitatory and interference effects may be of particular interest when studying groups in which multisensory interactions are affected. Furthermore, this is the first study of the CCT to present stimuli at the participant’s approximate threshold level and constrain baseline unisensory performance. This was achieved using an adaptive staircase procedure (PEST), chosen due to the speed by which an approximate threshold can be determined (although other adaptive procedures, or the method of constant stimuli, could also be used). In previous studies of the CCT, the elevation judgment is suprathreshold and the error rate is low. Thus, the CE is typically observed in the RT and not always in the error data (see Spence & Walton, 2005). Indeed, many studies combine error rate and RT into a single inverse efficiency score to control for any speed-accuracy ‘trade-off’ (e.g. Shore et al., 2006; Spence et al., 2001), which circumvents the fact that low error rates may
preclude the use of parametric statistical analysis. In contrast, presenting the stimuli at approximate threshold in the current study enabled us to measure the CE via error rates rather than RT. This is an advantage when investigating visual-tactile interactions in groups that are liable to produce variable RT data.

As an exploratory analysis, additional distractors were presented 21cm and 42cm from the hand in the ipsilateral hemispace, while controlling for depth. Neither of these additional distractors produced a significant CE. This suggests that the spatial modulation of vision on touch is dependent on absolute distance between the stimuli, rather than being positioned in the opposite hemispace. Distractors presented 42cm from the participant’s hand, in both the same and opposite hemispace as the target, produced a reduced CE compared to those presented by the participant’s hand. Although not statistically significant, the CE did not entirely disappear when distractors were not presented at the stimulated hand. This is in line with previous studies of the CCT (e.g. Spence et al., 2001) and the previous observation that the temporal coincidence of crossmodal stimuli has a stronger effect on multisensory processing than spatial colocation (see Spence, 2013). In the present study, temporal and spatial modulation were measured independently. However, the current task could be used to investigate how temporal modulation may vary when distractors are presented in different spatial locations (for example, Stevenson, Fister, Barnett, Nidiffer, & Wallace, 2012).

This adapted version of the CCT was developed to measure visual-tactile interactions between, and within, participant groups. Firstly, we revealed variability in tactile thresholds across participants, but threshold did not correlate with multisensory interference as measured in the -30ms (Experiment 3) and 0cm (Experiment 4) conditions. This suggests that presenting tactile stimuli at threshold level was successful in matching task difficulty across the participants. Thus, the influence of visual distractors on tactile performance is likely to reflect genuine multisensory processing rather than differences in unisensory tactile performance. Secondly, tactile thresholds were positively correlated with self-reported autistic traits, suggesting that individuals with higher levels of autistic traits found the tactile task more difficult. Self-report of sensory processing issues are highly correlated with autistic traits in the non-clinical population (Robertson & Simmons, 2013). Thus, there are individual differences in sensory processing in the general population that may need to be considered when designing behavioural and psychophysical experiments. Moreover, the relationship
between tactile thresholds and autistic traits emphasises the importance of attempting to control unisensory performance when measuring visual-tactile interactions in heterogeneous groups which may differ in purely tactile performance. Indeed, a previous study has indicated that adults with ASC produced higher tactile simultaneity and temporal order judgement thresholds than non-clinical controls (Tommerdahl, Tannan, Holden, & Baranek, 2008).

The method developed in the current study presents an approach to exploring visual-tactile interactions where unisensory tactile ability may differ within and between groups. Constraining performance in this manner is particularly useful in exploring the visual-tactile interactions in heterogeneous populations that may produce variable response times. This newly adapted design was used in Chapter 4 to explore visual-tactile interactions in individuals with ASC.
Chapter 4

Investigating visual-tactile interactions over time and space in adults with autism

Parts of this chapter have previously been published as:


and presented at the following conference presentations:

Experimental Psychology Society, Newcastle Meeting (2014)

International Meeting for Autism Research, Atlanta, USA (2014)
"When I was a child I craved the feeling of being hugged but then I withdrew because I was overwhelmed by the tidal wave of sensation"

Temple Grandin a woman with ASC (Grandin, 1992, pg. 108).

4.1 Introduction
It has been suggested that the sensory symptoms which affect many people with autism spectrum conditions (ASC) may be related to alterations in multisensory processing. Typically, the likelihood of interactions between the senses increases when information is temporally and spatially coincident. We explored the limits of visual-tactile interactions in adults with ASC for the first time using the adapted version of the CCT which was developed in Chapter 3. The temporal (Experiment 4) and spatial (Experiment 5) modulation of visual-tactile interactions was investigated. This chapter begins with an overview of the literature investigating multisensory processing in ASC, the findings of Experiment 4 and 5 are then discussed.

4.1.1 Multisensory processing in ASC
It has been proposed that sensory symptoms in ASC may arise from a disruption in the interaction between the senses (Iarocci & McDonald, 2006). Effective multisensory interactions are integral in creating a coherent perception of our environment; it is important that only information originating from the same source interacts. Efficient processing of multisensory stimuli develops throughout childhood (Gori, Del Viva, Sandini, & Burr, 2008; Hillock-Dunn & Wallace, 2012). It is possible that abnormalities in neuronal development in ASC could disrupt the maturation of these processes, leading to altered multisensory processing.

There are a number of studies which have investigated multisensory interactions in ASC using audio-visual speech stimuli in the McGurk task (MacDonald & McGurk, 1978). When presented with speech sounds that do not match lip movements, participants with ASC report that they perceive the sound, rather than the fused multisensory percept. This could indicate general difficulties with multisensory processing (Smith & Bennetto, 2007), but could also be driven by problems with lip reading (Iarocci, Rombough, Yager, Weeks, & Chua, 2010; Taylor, Isaac, & Milne, 2010; Williams, Massaro, Peel, Bosseler, & Suddendorf, 2004). Importantly, the social and semantic stimuli used in this paradigm increases the difficulty of the task for individuals with ASC (for instance, see Dawson, Meltzoff, Osterling, Rinaldi, & Brown, 1998), independently of the multisensory demands. Tasks utilising low-level stimuli allow differences in multisensory processing to be explored, circumventing the difficulties that social and semantic stimuli can present to individuals with ASC.
Studies of multisensory processing in individuals with ASC using low-level stimuli have produced mixed findings and have largely focussed on the interaction between visual and auditory information\(^3\). Children with ASC do not show typical performance enhancements when presented with multisensory stimuli over what would be expected if the stimuli were processed independently (Brandwein et al., 2013). That is, participants with ASC produced fewer race model violations than NT controls. Furthermore, ERP recordings revealed less effective neural integration of the audio-visual stimuli in children with ASC. NT participants produced super additive ERPs in response to multisensory stimuli at 100-120ms post stimulus onset. The ASC group showed similar audio-visual integration to NT controls by 180-210ms. Delayed integration of tactile and auditory information has also been observed in children with ASC (Russo et al., 2010); ERPs were recorded while the participants completed a passive task in which they were presented with auditory and tactile stimuli while watching a silent film. NT children showed a super-additive neural response from around 150ms, however this was not observed until 300ms in the participants with ASC. These studies suggest that the efficiency and automaticity of multisensory integration is reduced in children with ASC. Consistent with this suggestion, a recent study indicated that children with ASC produced the illusory flash-beep percept (see section 1.8.2) less frequently than controls (Stevenson et al., 2014). Although, a number of previous studies in adults with ASC have observed typical illusory responses (Keane, Rosenthal, Chun, & Shams, 2010; van der Smagt, van Engeland, & Kemner, 2007).

There is evidence that multisensory facilitation may be reduced in adults with ASC (Collignon et al., 2013). Adults completed a visual search task in which non-spatially informative auditory information typically reduces RT and error rates (Van der Burg et al., 2008). Participants with ASC performed comparably in tone present and tone absent conditions, suggesting no benefit of introducing crossmodal information. However, contradictory findings have been observed using the same task (de Boer-Schellekens, Keetels, Eussen, & Vroomen, 2013). Participants with ASC produced a similar reduction in RTs as controls on trials which included the tone. The authors note that these conflicting findings may partially be attributed to differences in task instructions between the studies. In the deBoer study participants were explicitly instructed that the auditory stimulus would inform the colour change of the target. This may have

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\(^3\) note that the behavioural tasks discussed in this section have previously been described in Section 1.8.1
encouraged the participants with ASC to consciously attend to the beep, leading to the performance enhancement.

Further differences have been reported in children with ASC relative to controls when the temporal presentation of audio-visual stimuli has been manipulated. On a version of the flash-beep illusion in which the SOA was varied, participants with ASC produced responses consistent with the illusory percept over a wider range of SOA than controls (Foss-Feig et al., 2010). The authors of this paper operationalised a ‘temporal binding window’ as consecutive SOA over which the illusory flash beep response was given significantly more frequently than in a baseline (visual alone) condition. Contradicting Stevenson et al, participants with ASC produced illusory responses more frequently than controls. These multisensory interactions were displayed over ±150ms in NT children and ±300ms for children with ASC (where negative SOA indicates that beeps preceded the visual target; see Figure 4.1).

![Figure 4.1](image)

**Figure 4.1** Report of illusory double flashes on the flash beep illusion as a function of SOA for participants with ASC (squares) and NT (circles). The participants with ASC produced responses consistent with the illusion across a significantly wider range of stimulus offsets than controls. Figure from Foss-Feig et al (2010).

Similar findings were reported on a visual-auditory temporal order judgement task (TOJ; Kwakye et al., 2011). Participants indicated which of two flashes presented above or below central fixation was presented first. A staircase procedure was used to determine the participant’s 75% threshold for these visual TOJs. The participant then completed the visual TOJs at threshold level and were presented with task irrelevant auditory stimuli. Typically, a multisensory performance enhancement will be observed if the
auditory stimulus is presented near simultaneously with the second flash (Hairston et al., 2005; Hairston, Hodges, Burdette, & Wallace, 2006). Children with ASC showed significantly increased multisensory performance enhancements in comparison to NTs. Controls produced consecutive multisensory performance enhancements up to 150ms SOA, while participants with ASC produced this effect up to around 300ms. This suggests that the temporal modulation of audio-visual information may be reduced in ASC. However, no differences in temporal modulation were observed when this task was repeated in a slightly older group of adolescents and young adults with ASC (de Boer-Schellekens, Keetels, et al., 2013). The ASC group produced a greater performance enhancement in the multisensory condition. These performance enhancements were reduced at later SOA similar to controls. In summary, studies which have investigated multisensory processing in ASC have produced mixed findings. There is evidence that multisensory interactions are less efficient in ASC. Audio-visual temporal processing appears to be altered in children with ASC, but similar when adults are compared. The current study is the first to explore the spatial modulation of multisensory stimuli in ASC, in addition to temporal modulation.

4.1.2 The interaction between vision and touch in ASC
The following experiments are also the first to investigate low level visual-tactile interactions in ASC. Two previous studies have investigated the interaction between vision, touch and proprioception using the rubber hand illusion. Adults with ASC reported questionnaire ratings consistent with experiencing the illusion at a similar level to controls (Paton, Hohwy, & Enticott, 2012). However, the participants with ASC showed less proprioceptive drift towards the rubber hand, which could suggest that they were less influenced by the visual stimuli. However, this potentially interesting finding was compromised as no pre-illusion baseline measure of the participants hand position was taken, meaning that this effect may simply reflect differences in the ability to localise hand position. A delay in experiencing the illusion was observed in children with ASC (Cascio et al., 2012). Children with ASC produced responses consistent with the illusion after 6 minutes of touch, while the effect was observed in controls after 3 minutes. This would appear to support the suggestion that multisensory interactions are less efficient in ASC. Nevertheless, the rubber hand illusion involves making judgements about social stimuli which participants with ASC may be less inclined to attend. Similar to studies exploring the interaction between auditory and visual information, it is beneficial to use low-level stimuli to characterise the interaction between vision and touch in ASC. A recent study examining tactile temporal order judgements between the hands has indicated that children with ASC do not produce the typical performance
detriment when their hands are crossed (Wada et al., 2014). Although this is a purely tactile task, the hands crossed effect has been attributed to the visual frame of reference affecting tactile perception, which suggests that this multisensory effect may be atypical in ASC. It is important to investigate visual-tactile processing as abnormalities may contribute to an aversion to being touched in ASC (see O’Neil and Jones, 1997), and could have implications for the alterations in motor control seen in ASC (Gowen & Hamilton, 2013). Visual-tactile interactions can provide a proxy measure of how near body (peripersonal) space is represented; being more likely to occur when visual stimuli are presented within the peripersonal space surrounding the hand (see Spence, Pavani, Maravita, & Holmes, 2004). Peripersonal space plays a subtle, but important role in social interaction. Typically we do not allow strangers to encroach our peripersonal space, and it can be disturbing if they do so. The representation of peripersonal space in ASC may affect higher level social behaviour, for instance, in maintaining socially appropriate distances (see Lloyd, 2009; further discussion of peripersonal space is included in section 6.1.1).

4.1.3 Aims and predictions
We explored two aspects of visual-tactile processing in a sample of adult participants with ASC and matched NT controls. Firstly, we aimed to determine whether the temporal modulation of visual-tactile interactions is disrupted in participants with ASC, as has previously been reported for audio-visual interactions (Foss-Feig et al., 2010; Kwakye et al., 2011; Stevenson, Siemann, Schneider, et al., 2014). Second, we sought to provide novel insight into the spatial modulation of multisensory interactions in ASC. In order to do so, we used the adapted version of the CCT (Spence et al., 1998), which was developed in Experiments 2 and 3. Participants were asked to judge whether they felt a single or double tactile vibration while presented with distracting light flashes (Holmes et al., 2006). Distractors were congruent (e.g. one vibration, one flash) or incongruent (one vibration, two flashes). As with the typical version of the task, the difference between the congruent and incongruent conditions gives the CE.

4.1.4 Methodological considerations
As discussed in Chapter 3, in the present version of the task, unisensory (tactile) performance was measured and thresholded so that performance across participants was fixed at around 75% accuracy. There were a number of reasons for adopting this technique: firstly, any confounds relating to differences in tactile performance that may exist between the groups were removed (Blakemore et al., 2006; Puts, Wodka, Tommerdahl, Mostofsky, & Edden, 2014). Furthermore, tactile thresholds have
previously been found to positively correlate with autistic traits in NT participants (Poole, Couth, Gowen, Warren, & Poliakoff, 2015), and presenting stimuli at each participant’s threshold should also reduce variability in tactile performance within the control group. Secondly, this enabled the CE to be measured through error rates rather than reaction times. Reaction time data can be variable in participants with ASC (Geurts et al., 2008) and this could potentially mask any differences in multisensory processing between the groups. Finally, comparing performance in conditions including visual distractors to unisensory performance provides an additional measure of multisensory interactions, specifically facilitation effects driven by congruent distractors can be separated from interference effects in response to incongruent distractors.

4.2 Method

4.2.1 Participants
18 participants with ASC (2 female) plus 18 NT controls matched for age, sex, handedness and IQ took part in the study. Experiments 2 and 3 reported a significant effect of temporal and spatial modulation of visual-tactile interactions in 13 NT participants (Poole et al., 2015). In the present study we aimed to exceed this sample size to find a between groups effect and account for the heterogeneity likely in participants with ASC. Autistic traits were measured in our NT sample using the AQ (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001). AQ responses ranged from 9 - 28. No participants exceeded the cut-off of 32 which is believed to indicate clinical significance. All participants had a full scale IQ > 80 measured using the Wechsler Abbreviated Scale of Intelligence (WASI, Weschler, 1999) and were aged 19-42 (see Table 4.1 for participant characteristics). Four participants with ASC and four controls were classified as left handed using the Edinburgh Handedness Inventory (EHI, Oldfield, 1971). One participant with ASC (female, right handed) was excluded from Experiment 5 prior to analysis due to responding randomly through fatigue (baseline accuracy rate = 40%), and was unavailable to return for a second session.
Table 4.1 Characteristics of participants with ASC and NT, including t-test statistics. Mean ± standard deviations values are presented.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>ASC</th>
<th>NT</th>
<th>t(34)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>29.8 ± 8.1</td>
<td>29.1 ± 7.2</td>
<td>.23</td>
<td>.819</td>
</tr>
<tr>
<td>FSIQ</td>
<td>118.3 ± 9.9</td>
<td>117.6 ± 13.4</td>
<td>.05</td>
<td>.960</td>
</tr>
<tr>
<td>AQ</td>
<td>-</td>
<td>17.61 ± 5.63</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ADOS</td>
<td>9.00 ± 1.75</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Low registration</td>
<td>37.11 ± 6.27</td>
<td>45.22 ± 7.54</td>
<td>3.56</td>
<td>.001 *</td>
</tr>
<tr>
<td>Sensory seeking</td>
<td>44.89 ± 8.15</td>
<td>34.67 ± 7.26</td>
<td>3.97</td>
<td>&lt;.001 *</td>
</tr>
<tr>
<td>Sensory avoidance</td>
<td>45.17 ± 9.95</td>
<td>37.78 ± 8.09</td>
<td>2.44</td>
<td>.020</td>
</tr>
<tr>
<td>Sensory sensitivity</td>
<td>42.56 ± 7.65</td>
<td>37.06 ± 5.78</td>
<td>2.44</td>
<td>.020</td>
</tr>
<tr>
<td>Tactile Temporal Threshold (ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 4</td>
<td>25.82 ± 12.67</td>
<td>26.06 ± 5.82</td>
<td>0.70</td>
<td>.944</td>
</tr>
<tr>
<td>Experiment 5</td>
<td>28.24 ± 11.73</td>
<td>26.50 ± 7.21</td>
<td>(33). 53</td>
<td>.599</td>
</tr>
</tbody>
</table>

4.2.2 Stimuli and apparatus
The stimuli and apparatus were identical to Experiment 2 and 3 (see section 3.2).

4.2.3 Procedure
To confirm sensory symptoms in our ASC sample all participants completed the Adolescent/Adult Sensory Profile (AASP; Brown & Dunn, 2002). The AASP is a self-report Likert style questionnaire measuring trait sensory processing. Items are divided into four quadrants (low registration, sensation seeking, sensory sensitivity and sensation avoiding), across categories of sensory processing e.g. touch processing (see Table 4.1).

Threshold procedure
The threshold procedure is described in detail in section 3.3.3. To fix unisensory tactile performance at around 75% accuracy experimental stimuli were delivered at approximate threshold level determined prior to the experimental procedure. Participants received two successive tactile stimuli in a two interval forced choice procedure using a constant (single) vibration and two separate (double) 80ms vibrations separated by a 0-200ms period of silence. The participant was instructed to indicate which interval contained the double vibration. An adaptive staircase procedure (PEST; see Taylor & Creelman, 1967) was used to determine the duration required between two vibrations for the participant to correctly identify a double vibration 75% of the time. Breaks were included after 90 and 180 trials. To ensure that the threshold procedure was not unduly long, if the participant had not reached the minimum step size by 180 trials, the program ended and an average of the participant’s reversals since
the 90th trial was taken. The procedure continued using this average level at the minimum step size of 1ms for 20 further trials (Experiment 4, ASC n = 1; Experiment 5, ASC n = 1, NT n = 1). Their threshold was taken as the average gap size across these trials.

**Experimental Procedure**
Participants were asked to make speeded responses upon the presentation of a target vibration, responding by lifting their toe in response to single vibrations, and heel in response to double. Throughout the experimental procedure, vibrations were presented at threshold level for that participant. The task included both baseline trials and trials with task irrelevant distracting LED light flashes, which were either congruent (e.g. single vibration, single light flash) or incongruent (e.g. single vibration, double light flash). Participants were explicitly instructed to ignore the light flashes as much as possible.

The procedure of Experiment 4 was identical to Experiment 2, with distractors presented at -30ms, 100ms, 200ms and 400ms SOA. The procedure of Experiment 5 was identical to Experiment 3, with distractors presented at 0cm, 21cm, 42cm and 42cm_opp relative to the tactile target. An enforced break was included after each block. Participants completed the AASP during a substantial break between the experiments. The order of testing was counterbalanced within the groups to avoid either experiment being unduly affected by fatigue or practice effects.

**Practice procedure**
Before the experimental procedure began, there were three practice blocks to familiarise participants with the task and ensure that the threshold procedure had worked effectively. The protocol for the practice procedure is described in section 3.3.3. Participants were required to perform at 75% accuracy ±10% in baseline trials on the third block to continue to the experimental task proper where each error represented a 5% reduction in performance accuracy. Participants who performed at 60% or 90% accuracy had the gap duration increased or decreased by 1ms and were required to repeat the practice procedure (Experiment 4, ASC n = 3; Experiment 5, ASC n = 3, NT n = 1). Participants who performed outside of these parameters completed a shortened version of the threshold procedure in which they were re-entered at the final step size reached (Experiment 4, ASC n = 3, NT n = 4; Experiment 5, ASC n = 1, NT n = 1). The initial gap size was set at ±8ms on this shortened threshold procedure.
**Visual task**
At the end of the experiment there was a short visual task to ensure all participants could detect single and double light flashes at each location. There was no difference in performance between the groups (see Appendix D1 for more details).

The entire experiment lasted approximately two hours.

**4.2.4 Data analysis**
Analysis was similar to that reported in 3.3.4. Performance accuracy was calculated for each participant in each condition. Trials longer than 2000ms (Experiment 4; ASC (3.05% of trials), NT (0.01%). Experiment 5; ASC (1.67%), NT (0.37%)), or under 150ms (Experiment 4; ASC (1.33%), NT (0.24%). Experiment 5; ASC (1.33%), NT (0.17%)) were removed from analysis. These errors were likely caused by lapses in attention or foot pedal errors and were not included in the error rate (Holmes, Sanabria, Calvert, & Spence, 2007; Shore et al., 2006). Data point outliers ±2SD from the group mean of that condition were replaced with the maximum or minimum value ±2%. In Experiment 5 a square root transformation was used to correct positive skew in the CE data (Shapiro-Wilks p > .023). Multisensory performance was contrasted with unisensory performance, using paired sample t-tests to compare accuracy in each condition with the baseline condition of that experiment (Figure 4.3). In an additional analysis Pearson’s correlation coefficients were calculated to investigate the relationship between NT participant’s responses to items on the AASP and AQ. The relationship between AQ scores, tactile thresholds and the size of the CE in each SOA and position were also explored using Pearson’s correlation coefficients.

**4.3 Results**

**4.3.1 Tactile Temporal Acuity**
Tactile temporal separation thresholds revealed no significant group differences for the temporal or spatial tasks (Table 4.1).

**4.3.2 Experiment 4**
The CE was larger for distractors presented at -30ms than at later SOA (Figure 4.2). The Group x SOA interaction was the critical test to determine whether the temporal modulation of visual-tactile interactions differed between the groups, but this interaction was not statistically significant.
A mixed ANOVA [SOA (-30ms, 100ms, 200ms, 400ms) x Group (ASC, NT)] revealed a significant effect of SOA ($F(3, 102) = 18.14, p < .001, \eta_p^2 = .348$) indicating that the size of the CE varied across SOA. To follow up the significant effect of SOA data was pooled between the groups and paired sample t-tests (Bonferroni corrected, $\alpha = .008$) were conducted to compare the congruency effect between SOAs. The CE was significantly larger at -30ms than at 100ms ($t(35) = 3.78, p = .001, d = 0.68$), 200ms ($t(35) = 5.68, p < .001, d = 1.24$) and 400ms ($t(35) = 5.27, p < .001, d = 1.38$). The congruency effect was significantly larger at 100ms than at 200ms ($t(35) = 3.00, p = .005, d = 0.64$) and 400ms ($t(35) = 3.15, p = .003, d = 0.78$), but did not differ between 200ms and 400ms ($t(35) = .49, p = .622, d = 0.12$). There was no main effect of Groups ($F(1, 24) = .100, p = .754, \eta_p^2 < .001$) suggesting the CE was comparable between participants with ASC and NT. The interaction between Group and SOA, was not significant ($F(3, 102) = .88, p = .453, \eta_p^2 = .025$) indicating that the CE across the SOA was similar between the groups.

Paired sample t-tests (Bonferroni corrected, $\alpha = .006$) were conducted to compare performance of congruent and incongruent distractors with baseline performance (Figure 4.3). The effects of the distractors were similar for each group with (near) simultaneous incongruent distractors leading to an increased error rate. Participants with ASC produced an error rate significantly greater than baseline to incongruent distractors presented at -30ms ($t(17) = 3.19, p < .005, d = 0.92$). There was a trend towards congruent distractors presented at 200ms ($t(17) = 2.33, p = .033, d = 0.80$) and incongruent distractors presented at 400ms ($t(17) = 2.75, p = .014, d = 0.41$) producing a lower error rate than baseline. No other differences reached statistical significance ($t < 2.04, p < .058$). NT participants produced an error rate significantly greater than baseline to incongruent distractors presented at -30ms ($t(17) = 5.22, p < .001, d = 1.76$) and 100ms ($t(17) = 3.17, p = .006, d = 0.88$). No other differences reached statistical significance ($t < 1.06, p > .304$).

4.3.3 Experiment 5
The CE was marginally larger for the distractors presented by the participants hand than at more distant positions (Figure 4.2). The Group x Position interaction was the critical test of differences in spatial modulation of visual-tactile interactions between the groups. There was a trend towards a between group difference in the size of the CE across the positions, but this was not statistically significant.

A mixed ANOVA [Position (0cm, 21cm, 42cm, 42cm_opp) x Group (ASC, NT)] revealed a significant effect of Position ($F(3, 99) = 2.66, p = .052, \eta_p^2 = .075$) indicating that the size of the congruency effect varied across the different positions. Paired sample t-tests
Bonferroni correction, α = .008) revealed that there was a trend towards a larger congruency effect to distractors presented at 0cm over 42cm (t (35) = 2.58, p = .014, d = 0.37) and 21cm over 42cm (t (35) = 2.17, p = .037, d = 0.26). No other differences reached statistical significance (t < 1.11, p > .276). There was no main effect of group (F (1, 33) = .41, p = .524, η² = .01), suggesting the CE was similar for participants with ASC and NT. The interaction between Position and Group was approaching significance (F (3, 99) = 2.51, p = .063, η² = .071), suggesting that the effect of position on CE tended to differ between participants with ASC and NT.

Paired sample t-tests (Bonferroni corrected, α = .006) were conducted to compare performance in each condition with baseline performance (Figure 4.3). Incongruent distractors positioned close to the stimulated hand lead to an increased error rate for both groups, but participants with ASC also produced this effect to the distractor in the opposite hemispace. Participants with ASC produced an error rate significantly greater than baseline to incongruent distractors presented at 0cm (t (16) = 5.78, p < .001, d = 1.34), 21cm (t (16) = 4.57, p < .001, d = 1.14) and 42cm_opp (t (16) = 3.42, p = .003, d = 0.98). The increase in error rate in response to the 42cm light was approaching significance (t (16) = 2.97, p = .009, d = 0.83). No other differences reached statistical significance (t < 1.37, p > .189). NT participants produced an error rate significantly greater than baseline to incongruent distractors presented at 0cm (t (17) = 3.43, p = .003, d = 0.86) and 21cm (t (17) = 3.49, p = .003, d = 0.83). The difference was approaching statistical significance for distractors presented at 42cm (t (17) = 2.86, p = .011, d = 0.61) and 42cm_opp (t (17) = 2.67, p = .016, d = 0.60).
Figure 4.2 Congruency effect (% error) at each SOA (Experiment 4, A) and position (Experiment 5, B). The congruency effect is calculated by deducting the error rate in incongruent trials from congruent trials for each group at each position. ASC participants are represented by dark grey bars, NT participants are represented by lighter grey. Error bars represent standard error of the condition means.
Figure 4.3 Mean error rate for congruent (diamonds) and incongruent trials (squares) at each SOA (Experiment 4, A), and position (Experiment 5, B) for ASC and NT participants. Mean error rate in the unisensory baseline condition is represented for each group in each experiment by the solid black line. Asterisks denote a significant difference from baseline (Bonferroni corrected, $\alpha = .006$). Within participants 95% confidence intervals (Cousineau, 2005) are represented in each distractor condition by error bars and in the Baseline condition by the dotted line.

4.4.4 Relationship with questionnaire data
Pearson’s correlation coefficients (Bonferroni corrected $\alpha = .013$) were calculated to investigate the relationship between AQ scores and AASP scores (see Figure 4.4). There was no significant correlation with sensory seeking items ($r = -.20, p = .431$), low
registration items ($r = .49, p = .037$) or sensory sensitivity items ($r = .48, p = .043$). There was a moderate to strong positive correlation with sensory avoidant items ($r = .67, p = .002$).

**Figure 4.4** The AQ scores for the NT participants plotted as a function of scores from each quadrant of the AASP: sensory seeking, low registration, sensory avoidance and sensory sensitivity. There was a significant positive correlation with sensory avoidance items. To illustrate the spread of scores, the data in the figure is not adjusted for outliers.

Pearson’s correlation coefficients (Bonferroni corrected $\alpha = .025$) were calculated to investigate the relationship between AQ score and both tactile thresholds and CEs. AQ score did not correlate significantly with thresholds in Experiment 4 ($r = .38, p = .116$) or Experiment 5 ($r = .26, p = .299$), or with the size of the CE for any SOA, or position ($r < .33, p > .178$; see Appendix D2).

### 4.5 Discussion

Experiments 4 and 5 compared the temporal and spatial modulation of visual-tactile interactions between adults with high-functioning ASC and a matched NT control group. Evidence of altered sensory function was confirmed in participants with ASC using the AASP (Brown & Dunn, 2002). Compared to NT participants, those with ASC rated low registration items significantly more highly and sensory seeking items significantly lower (see Table 4.1). There was no significant difference in tactile temporal separation thresholds between the groups. In the temporal task (Experiment 4), the congruency effect (CE) was significantly larger when stimuli were presented near simultaneously (-30ms) than at all other stimulus onset asynchronies (SOA) for both groups. Comparisons
with a unisensory baseline revealed evidence of multisensory interactions at -30ms and 100ms for NT, but only -30ms for ASC participants. The NT group exhibited a significantly increased error rate to incongruent distractors presented 100ms after the target in comparison to baseline trials, but this was absent in the group with ASC. In the spatial task (Experiment 5), the congruency effect was significantly larger for visual stimuli presented 0cm and 21cm compared to 42cm from the participant’s hand. The baseline analysis revealed evidence of multisensory interactions for participants with ASC for visual stimuli presented 0cm and 21cm from the participant’s hand and at a position 42cm from the participant’s hand in the opposite hemispace. NT participants produced this effect only for visual distractors positioned at 0cm and 21cm.

The between-group differences in trait sensory processing as measured by the AASP is consistent with previous self-reports in high-functioning adults with ASC (Crane et al., 2009). Furthermore, there was a significant positive correlation between AQ score and sensory avoidance in the control group. This is in line with recent research which has suggested that autistic traits may be associated with altered sensory functioning in the NT population (Horder, Wilson, Mendez, & Murphy, 2014; Robertson & Simmons, 2013). It is important to characterise NT participants used as a control group since individual differences in sensory and autistic traits may potentially mask between-group differences on behavioural measures. However, it should be noted that there were no significant correlations between AQ scores and tactile thresholds (although see section 3.5.4), or the size of the CE at each SOA and position. This suggests that the null effect of group on the temporal modulation of visual-tactile interactions in Experiment 4 was not driven by the NT participants who reported above average levels of autistic traits.

Tactile stimuli were presented at threshold in an attempt to equate the task difficulty between, and within, the participant groups. To determine tactile thresholds we utilised a non-spatial task which relied on participant’s ability to separate vibrotactile stimuli in time and these thresholds did not differ statistically between the groups. Although it was not an explicit aim of the current study, this null difference contributes to the literature on the temporal processing of tactile stimuli in ASC. A previous study employed two tasks in which participants made simultaneity judgements and temporal order judgements regarding vibrotactile stimuli presented to different locations on the participant’s hands (Tommerdahl, Tannan, Holden, & Baranek, 2008). Adults with ASC produced higher thresholds than NT controls on both tasks when stimuli were delivered to the same hand, suggesting that longer durations were required to separate the vibrations (although see Puts et al., 2014, for different findings in children). When
stimuli were presented to different hands, performance was comparable to controls. It may be that the ability to separate vibrotactile stimuli in time is intact in adults with ASC, but issues arise when separating stimuli occurring at different positions on the same limb. The issue of how time and space interact when individuals with ASC process tactile stimuli merits further investigation.

Typical audiovisual temporal modulation has previously been reported in adolescents and young adults with ASC (de Boer-Schellekens, Keetels, et al., 2013) and the current study extends this to the visual-tactile modalities. Both groups produced a typical temporal profile of visual-tactile interactions previously established using the CCT (Shore et al., 2006). Interestingly, the findings from the baseline analysis suggest, that if anything, temporal modulation was stronger in participants with ASC. These findings contrast with reports of audiovisual interactions in children with ASC over a range of SOAs double in size to NT children (Foss-Feig et al., 2010; Kwakye et al., 2011). The temporal modulation of multisensory interactions appears to be a complex developmental process, maturing across childhood and into late adolescence in the NT population (Hillock-Dunn & Wallace, 2012). Therefore, a developmental delay in the temporal modulation of multisensory interactions in ASC may account for these apparently contradictory findings (see also, Stevenson, Siemann, Woynaroski et al., 2014). Although it is also plausible that compensatory strategies, for instance top-down attentional mechanisms (Talsma et al., 2010), may have been established by adulthood. Top-down selection may ‘step-in’ to regulate how multisensory stimuli are processed when separated in time, perhaps driven by the strength of association between pairs of stimuli. Experiment 6 was designed to further characterise unisensory and multisensory temporal processing in adults with ASC.

We also investigated spatial modulation of multisensory interactions in ASC for the first time and provide preliminary evidence that this may be affected. Both groups made significantly more errors in comparison to baseline when incongruent distractors were presented next to or 21cms away from the stimulated hand. Participants with ASC also showed this effect when distractors were presented in the opposite hemispace (the 42cm_opp position). However, there was considerable variability in performance in Experiment 5. Both groups of participants made more errors in response to the distractors in Experiment 5 than Experiment 4, and between-participant variability was much larger. Thus, selectively attending to touch in the presence of visual distractors presented at multiple, unpredictable locations (Experiment 5) appears to be more demanding than when distractors are presented in a predictable location, at different
time points (Experiment 4). These task demands may have disproportionately affected
the participants with ASC and thus the measurement of spatial modulation in this
population. Nevertheless, we consider alternate explanations for this potential
alteration in spatial modulation below.

The current findings could reflect a specific difficulty in the spatial processing of cross-
modal stimuli. The spatial modulation of visual-tactile interactions has previously been
shown to be affected in healthy ageing (Poliakoff et al., 2006). Older participants, aged
over 76, produced statistically comparable CEs in response to distractors presented at
the opposite and stimulated hand. Individuals with ASC may have similar issues
appropriately modulating visual-tactile interactions. This might imply that the
representation of peripersonal space around the hand is extended into the contralateral
hemispace in participants with ASC. Where responses to extraneous stimuli are not
effectively modulated or inhibited, perceptual estimates are likely to be noisy. Increased
noise is believed to contribute to sensory symptomology in ASC (Pellicano, 2013), for
instance, vision may have an atypical effect on the experience, or expectation of being
touched. Our findings also fit with the recent observation that tactile judgements are
less affected in participants with ASC when the arms are crossed over the body midline
(Wada et al., 2014). This suggests that tactile spatial representations may be less
affected by a visual frame-of-reference in ASC. The representation of peripersonal space
in ASC was explored further in Experiment 7.

It is also important to consider a more general attentional account for the influence of
more distant distractors in the ASC group. One possibility is that this finding reflects a
difficulty in selectively attending to one location that can also be observed purely within
the visual modality (Burack, 1994). Identifying the mechanisms which produce the
increased processing of distant distractors will help improve our understanding of
sensory processing in ASC. In Experiments 8 and 9, we explored whether similar effects
were observed within and across sensory modalities while considering the issue of
multiple distractor locations mentioned above.

In summary, the present study has revealed intact temporal modulation of visual-tactile
interactions in a group of adults with ASC with self-reported sensory symptoms. This
extends the characterisation of the temporal aspects of multisensory interactions in ASC
to visual-tactile interactions in an adult sample. We also provide evidence that the
spatial modulation of these interactions may be altered in ASC. These findings are
explored in further depth in Experiments 6-9.
Chapter 5

Uni and multisensory temporal acuity in adults with autism spectrum conditions
‘Sometimes the channels get confused... Sometimes I know that something is coming in somewhere, but I can’t tell right away what sense it is coming through’

Jim a man with ASC (reported in Cesaroni & Garber, 1991 p 305)

5.1 Introduction

In Experiment 4, both participants with ASC and NT produced multisensory interactions when visual-tactile stimuli were presented near simultaneously, but not at greater temporal discrepancies. This suggests that the temporal modulation of visual-tactile interactions may be intact in adults with ASC, which contradicts previous research in children with ASC in the auditory-visual modalities (de Boer-Schellekens, Eussen, & Vroomen, 2013; Foss-Feig et al., 2010; Kwakye et al., 2011). There may be a developmental delay in the temporal modulation of crossmodal stimuli which has normalised by adulthood in ASC. Alternatively, it may be that interactions between vision and touch are typical, while the auditory-visual modalities may be affected. To expand upon our findings from Experiment 4 multisensory temporal processing was explored using an alternative task, and also included auditory-visual and tactile-auditory pairings. Unisensory temporal acuity was also investigated. The literature on temporal sensitivity to multisensory stimuli in NT and ASC individuals is reviewed below before the design of Experiment 6 is introduced.

5.1.1 Multisensory temporal sensitivity in NT

Temporal Order Judgement (TOJ) and Simultaneity Judgement (SJ) tasks have been used to explore temporal sensitivity to crossmodal stimuli (Stone et al., 2001; Vroomen, Keetels, de Gelder, & Bertelson, 2004; Zampini, Guest, Shore, & Spence, 2005; Zampini, Brown, et al., 2005). In a typical crossmodal TOJ task the participant is presented with stimuli from two different sensory modalities and is required to indicate which came first. The stimuli are separated by a range of SOAs and data can be fitted by a Psychometric function to extract measures of temporal sensitivity between the senses (typically the participant’s Just Noticeable Difference; JND), and bias towards a particular sense (Point of Subjective Equality; PSE. See Figure 5.1.). Alternatively, in an SJ task participants are presented with crossmodal stimuli separated by a range of SOA and are asked to respond whether the stimuli were simultaneous or sequential (Figure 5.1). The data can be fitted by a Gaussian function and the SD of this function can then be used as a measure of sensitivity and the mean of the function gives the point of subjective simultaneity (PSS).
An early study explored visual-tactile, auditory-visual and tactile-auditory TOJs, reporting JNDs of approximately 20ms for each bimodal pairing (Hirsh & Sherrick, 1961). However, it has subsequently been noted that sensitivity may have been overestimated as the stimuli in this study were presented from different positions making the task easier (the spatial separation of stimuli in crossmodal TOJ tasks is discussed in detail in Chapter 6). Subsequent studies have reported JNDs of 46ms for visual-tactile, 53ms for auditory-visual and 75ms for tactile-auditory stimuli when both are presented from the same location (Spence et al., 2003; Zampini et al., 2005). It is worth noting that the calculation of JNDs tends to differ between studies, making direct comparisons difficult to interpret (Fiacconi, Harvey, Allison, & Bennett, 2013). In the present study JNDs are calculated in the same way as Zampini, Shore, and Spence (2003a;2003b) and Zampini et al. (2005) as detailed in Appendix A.
Multisensory temporal sensitivity appears to be affected over the lifetime. Auditory-visual SJ tasks, have revealed that the temporal sensitivity of children and adolescents is significantly reduced in comparison to young adults (Hillock, Powers, & Wallace, 2011; Hillock-Dunn & Wallace, 2012). Older participants produced larger JNDs on a visual-tactile TOJ (Polakoff, Shore, Lowe, & Spence, 2006), although performance on an auditory-visual task has been shown to be comparable with young controls (Fiacconi et al., 2013). These studies suggest that there are age-related changes leading to the maturation and decay of multisensory temporal sensitivity. This process may occur at different rates between individuals or sensory pairings.

Typically the PSE measured in TOJ tasks is not at objective simultaneity (i.e. zero separation between the stimuli). The PSE tends to vary between individuals (Stone et al., 2001), and can be influenced by a number of factors. The reduced transduction rate of vision in comparison to the other modalities is believed to cause the PSE to move towards vision when presented with auditory or tactile information (Spence, Baddeley, Zampini, James, & Shore, 2003; Zampini, Shore, & Spence, 2003), meaning visual stimuli need to be presented earlier than tactile or auditory to be perceived as simultaneous. The PSE may also shift towards the modality to which the participant is attending. This can be experimentally manipulated with explicit instruction to attend to a particular modality in the pairing (Spence, Shore, & Klein, 2001). Furthermore, the PSE can also be affected by certain stimulus parameters. For instance, when participants are presented with auditory-visual stimuli of 9, 40 and 500ms durations the participant’s PSE will tend to shift towards a common value, closer to objective simultaneity, at longer stimulus durations (Boenke, Deliano, & Ohl, 2009).

5.1.2 Tasks measuring the temporal separation of crossmodal stimuli in ASC
Two previous studies have explored the temporal acuity of auditory-visual stimuli in ASC. These experiments used stimuli of varying complexity including a flash-beep, McGurk stimuli and complex, but not social auditory-visual stimuli. Participants aged 6-18 completed a SJ task (with the non-social stimuli a hammer striking a surface; Stevenson et al., 2014), and participants aged 16-22 using similar stimuli in a TOJ task (with the non-social stimuli a handclap; de Boer-Schellekens et al., 2013). Both studies indicated that sensitivity was reduced with increasing stimulus complexity, and that participants with ASC produced larger JNDs than controls (although this effect was statistically marginal in the Stevenson et al., 2014 study). This suggests that multisensory temporal sensitivity to auditory-visual stimuli may be reduced in ASC. Furthermore, sensory processing issues with touch and hearing are frequently reported
in ASC (Kern et al., 2006). If temporal sensitivity is reduced between the senses this would lead to a disrupted perception of one’s multisensory environment and could contribute to atypical sensory experiences. However, no research to date has investigated temporal processing for tactile-auditory stimuli in ASC.

Accurate performance on TOJ tasks involves making a judgement about the relative temporal presentation of the stimuli. Experiments 2 and 4 involved making judgements about a target while inhibiting the effect of a distractor presented at different temporal discrepancies. These tasks provide an indirect measure of multisensory temporal sensitivity as it is assumed that the senses must be in temporal alignment to interact. As the TOJ task is a more direct measure of multisensory temporal sensitivity, we chose to use TOJs with low-level stimuli in a group of adult participants with ASC to expand the characterisation of temporal acuity across the sensory modalities.

TOJ tasks were utilised over SJ, as they are less likely to be affected by cognitive biases. Participants may be more, or less, inclined to report stimuli presented in close temporal proximity as simultaneous in an SJ task. Accordingly, measures extracted from SJ and TOJ data do not necessarily map onto one another (see Vroomen & Keetels, 2010). We considered that these biases might contaminate the measurement of the separation of crossmodal stimuli in ASC, particularly if the groups differ in their level or direction of bias. For instance, if participants with ASC were simply biased towards reporting stimuli as being simultaneous when presented close together in time, then temporal sensitivity would appear to be reduced. This issue is reduced on a TOJ task as the participant is required to make a decision as to which of a choice of modalities were presented first. Other experimental considerations were taken into account in the design of Experiment 6. Firstly, stimuli were presented from a single spatial location to minimise any beneficial effects of spatial separation on the participant’s temporal sensitivity. Second, participants were asked to state which modality was presented first in each pairing rather than encouraging the participant to specifically attend to vision, touch or hearing. The participant was required to say, for example, if vision was first or second in a bimodal pairing. It was also considered that reduced multisensory temporal acuity may be part of a general issue with separating stimuli in time rather than a multisensory deficit. There is some evidence that general timing sensitivity is reduced in ASC (Falter, Noreika, Wearden, & Bailey, 2012; Martin, Poirier, & Bowler, 2010; although see Falter, Braeutigam, Nathan, Carrington, & Bailey, 2013; Falter, Elliott, & Bailey, 2012 for evidence of enhanced ability to separate unisensory stimuli using SJ tasks). In Experiment 6 participants also completed visual, tactile and auditory temporal acuity
threshold procedures to explore whether any differences in temporal processing would also be observed for unisensory judgements.

5.1.3 Experiment 6 aims and hypothesis
Multisensory temporal acuity in ASC was investigated in Experiment 6 using bimodal TOJ tasks. It was anticipated that sensitivity (measured using JNDs) would be reduced for visual-auditory and auditory-tactile pairings, as has previously been reported for auditory-visual information in younger participants (de Boer-Schellekens, Eussen, et al., 2013; Stevenson, Siemann, Schneider, et al., 2014). Sensitivity to the visual-tactile TOJs was not expected to differ between the groups as Experiment 5 indicated that the temporal modulation of visual-tactile stimuli was intact in ASC. PSE data was predicted to vary within and between participant groups. As PSE data indicates bias towards a sensory modality, we explored the relationship between PSE and sensory symptoms in participants with ASC. Unisensory temporal acuity thresholds were included as a control task for general temporal acuity in ASC, but due to equivocal previous work it was not possible to predict differences between groups.

5.2 Experiment 6 Method
5.2.1 Participants
The participant demographic information is included in Table 5.1. The intended sample size was 18 participants in each group based on Experiments 4 and 5. Experiments 6 to 9 were run as part of a testing battery over two separate sessions. The multisensory TOJ tasks reported in Experiment 6 and Experiment 7 were included in the first session. The unisensory threshold procedures, Experiments 8 and 9 were run in the second session. In addition to the standard visual tests (see 2.2.1), no participants showed red-green perception deficiencies (Ishihara, 1979). A participant with ASC (male, 42 years old) left before Experiment 8 and 9 in the second session and was unavailable to return for an additional visit. 8 participants with ASC and 1 control had previously participated in Experiments 4 and 5.

| Table 5.1 Participant characteristics for Experiments 6, 7, 8 and 9. |
|-----------------|-----------------|-------|-----|
|                | ASC (n = 18)    | NT (n = 18) | t(34) | P   |
| Age            | 31 ± 8.43       | 31.05 ± 8.71 | .02   | .985|
| FSIQ           | 116.56 ± 9.67   | 112.18 ± 7.56 | 1.49  | .147|
| AQ             | -               | 16.45 ± 7.19  | -     | -   |
| ADOS           | 8.55 ± 2.28     | -             | -     | -   |
| GSQ score      | Total           | 76.06 ± 24.28 | 1.44  | <.001|
|                | Hyper sensitivity | 38.56 ± 14.47 | 16.78 ± 9.65 | 5.31  | <.001|
|                | Hypo sensitivity | 37.50 ± 12.42 | 14.67 ± 8.83 | 6.38  | <.001|

(Bonferroni corrected, α = .013)
5.2.2 Apparatus
Participants sat at a desk in a dimly lit room and were instructed to focus on a central fixation point consisting of a silver cross (10mm) in the centre of the screen. A speaker was used to present sound files (sine wave, 440Hz, 0.8 AMPs) from a PC through a Tacamp amplifier (Dancer Design, St. Helens UK). A 65mm x 85mm foam block was positioned 25mm in front of the speaker. A bone conductor (Oticon Limited, B/C 2-PIN, 100Ω, Hamilton, UK) which was driven by the same sound files was embedded in the foam cube and attached to the participant’s index finger on their dominant hand using double sided adhesive. A single red LED (10mm in diameter), embedded in a black plastic cube (25mm), was positioned at the tip of the participants index finger (see Figure 5.2).

White noise (~75dB SPL) was played through headphones throughout the experiment to prevent the participant from hearing sounds emitted by the bone conductor. The beeps from the speaker were clearly audible over the white noise. This was confirmed by each participant before beginning the experiment.

Participants also completed the Glasgow Sensory Questionnaire (Robertson & Simmons, 2013) which is described in Chapter 2.2.1.

Figure 5.2 Schematic of the experimental set-up for a right handed participant. The participant held a tactor, which was embedded in a foam cube using the thumb and forefinger of their dominant hand. An LED was positioned next to the tactor on the foam cube. The speaker was placed behind on a separate foam cube to prevent the participants feeling vibrations emitted by the speaker through the table. The participant was instructed to fixate on a grey cross positioned 19 cm above the speaker.

5.2.3 Stimuli
The stimuli used in the unisensory temporal acuity procedure and multisensory TOJS were identical. The overall duration of single and double stimuli on the unisensory threshold tasks were matched to ensure participants could not distinguish between the stimuli using overall duration. Visual stimuli comprised a single flash or two 8ms flashes separated by a gap during which the light was off. Auditory stimuli (sine wave, 440Hz, 0.8 AMPs) comprised a single beep or two 8ms beeps separated by a gap of silence. Tactile stimuli (sine wave, 440Hz, 0.8 AMPs) comprised a single vibration or two 8ms pulses separated by a gap of no stimulation. All stimuli were clearly suprathreshold.

5.2.4 Procedure

**Unisensory temporal acuity thresholds**

Participants completed separate procedures to determine their approximate visual, auditory and tactile thresholds. Participants received two successive stimuli in a two interval forced choice procedure using constant stimulation (single) and two separate (double) 8ms periods of stimulation separated by a 0-200ms gap. Participants were asked to respond to which interval contained the double stimulation by lifting their toe or heel from the foot pedal (see Figure 5.3).

![Diagrammatic representations of visual, auditory and tactile threshold trials](Figure 5.3)

The procedure for each modality was identical; an adaptive staircase procedure (PEST; see Taylor & Creelman, 1967) was used to determine the duration required between two stimuli for the participant to correctly identify the double stimuli 75% of the time. This procedure has been described in detail in Chapter 3.3.3. Participants began at the maximum gap size of 200ms and the initial step size corresponded to a 32ms reduction in the gap duration. The procedure came to an end when the participant reached the minimum step size, which corresponded to 1ms in gap duration. After reaching the
minimum step size, 20 further trials were included over which the average of the reversals was taken as the threshold value. The participant’s accuracy was checked over these trials to confirm that the threshold procedure had reached the expected level of performance (i.e. 75% ± 10). The number of trials on each procedure was capped at 100. If participants reached 100 trials their threshold was taken as the average of the values presented over the previous 20 trials (visual ASC n = 10, NT = 8; Auditory ASC n = 10, NT n = 6; Tactile ASC n = 5, NT = 4). If participants had reached 100 trials without reaching a step size lower than 10ms they were excluded from analysis (visual NT n = 2; auditory, ASC n = 3; tactile ASC n = 1, NT = 1). It was likely that the procedure had not determined an average level of performance for these participants. Time series for participants that reached 100 trials are included in Appendix E1.

The procedure for each modality was completed in separate blocks, with the order of testing counterbalanced between participants. This took approximately 45 minutes.

Bimodal TOJs
The task required participants to report the order of each bimodal pairing. Participants responded to which stimuli came first verbally, which was recorded by the experimenter (see Figure 5.4)

![Diagram](image)

*Figure 5.4 Diagrammatic representations of auditory-visual, visual-tactile and tactile-auditory TOJ trials.*

Single visual, tactile and auditory stimuli were used and were presented at ± 20ms, 55ms, 90ms, 200ms and 400ms SOA using the method of constant stimuli. For each stimulus pairing, each SOA was presented 10 times randomly across five blocks of 60 trials, giving 300 trials in total. Before the presentation of the stimuli there was a delay
interval randomly selected from a uniform distribution of 500-1000ms during which time the fixation cross remained visible. This was to prevent the participant from using the time between the beginning of the trial and the presentation of the second stimuli as an additional cue to determine temporal order. An onscreen prompt appeared to remind the participant which pairing had been presented 200ms after the stimulus presentation. The participant’s responses were un-speeded; they were encouraged to take their time in deciding which stimuli came first. There was then a delay of 1000ms after the experimenter entered the participant’s response, during which time the screen went blank, before the central fixation cross appeared to indicate the next trial was due to commence. Participants received no feedback during the experimental trials.

Before beginning the experimental trials, participants completed 8 trials of each bimodal pairing in a practice procedure divided equally into ±400ms SOA. Feedback was provided during the practice trials: incorrect responses were followed by an ‘incorrect’ sign. Participants continued to the experimental trials once the task instructions were understood and performance was at least 80% accurate for each condition.

5.2.5 Data analysis
For the unisensory thresholds, data points were removed where a participant did not perform at 75% accuracy ± 15 on the final 20 trials for a given modality i.e. ≥ 11 or ≤ 19 (visual ASC, n = 1; Auditory ASC n =1, NT n = 1), further to those removed as described in section 5.2.4. It is likely that the threshold procedure had not appropriately captured the participants’ threshold in these instances. The final sample sizes were: visual ASC n = 17; NT n = 14, auditory ASC n = 14; NT n = 17, tactile ASC n = 17; NT n = 17). The remaining groups did not significantly differ in age or IQ (p > .185; participant demographics are included in Appendix E2). In Experiment 6 a log transformation was used to correct positive skew in the threshold data (Shapiro - Wilks p < .023). A mixed ANOVA was used to explore differences in unisensory temporal acuity thresholds between the groups. Significant interactions were followed up with t-tests.

For the bimodal TOJs, responses for each stimulus pairing were converted to proportion of vision first (visual-tactile trials), auditory first (auditory-visual trials) and touch first (tactile-auditory trials). Each participant’s data was then fitted by a cumulative Gaussian Psychometric function (included in Appendix E3). Each participant’s JND \( \frac{0.675}{\beta} \) Zampini et al., 2003a, 2003b; Zampini, Brown, et al., 2005), and PSE were then extracted for each stimulus pairing. Participants that produced a standard deviation beyond the range of SOA were removed prior to analysis (auditory-visual ASC n= 1, tactile-auditory ASC n= 1).
Mixed ANOVAs were used to compare the JND and PSE between the groups. Significant interactions were followed up with t-tests. One sample t-tests were also used to compare the PSE with objective simultaneity for each stimulus pairing.

Multiple regressions were calculated for each group to explore the relationship between sensory scores reported using the GSQ and participants JND and PSE in each condition. Multiple regressions were also calculated to explore the relationship between autistic traits in the NT group and JND and PSE scores in each condition (this analysis is included in Appendix E4).

### 5.2 Experiment 6 Results

#### 5.2.1 Unisensory Thresholds

Threshold data is displayed in Figure 5. Cohen’s d measure of effect size is displayed comparing the thresholds between the groups for each modality. For both groups thresholds were lowest for auditory stimuli and highest for visual stimuli. A mixed ANOVA [Condition (Visual, Auditory, Tactile) x Group (ASC, NT)] revealed a significant effect of condition \(F (2, 48) = 113.18, p < .001, \eta_p^2 = .83\) indicating that the size of the thresholds differed between the conditions. To follow up the significant effect of condition, data was pooled between the groups and paired sample t-tests (Bonferroni corrected, \(\alpha =.017\)) were conducted to compare the thresholds between each condition. Visual thresholds were significantly larger than tactile \(t (30) = 10.07, p < .001, d = 2.36\) and auditory \(t (25) = 14.68, p < .001, d = 4.31\). The tactile threshold was significantly larger than the auditory \(t (28) = 5.88, p < .001, d = 1.31\).

There were two critical tests of between group differences in unisensory temporal acuity. There was no significant effect of group \(F (1, 24) = .47, p = .500, \eta_p^2 = .019\), meaning the size of thresholds did not differ between the groups. However, as can be observed in Figure 5.5 there was considerable variability in ASC participant thresholds. Second, the condition x group interaction did not reach significance \(F (2, 48) = .69, p = .507, \eta_p^2 = .028\), meaning the pattern of thresholds across the conditions did not differ significantly between participants with ASC and NT.
Figure 5.5 Thresholds for visual, tactile and auditory stimuli for participants with ASC (blue) and NT (red). The edges of each box represent the upper and lower quartile and the whiskers represent the most extreme deciles. The line within the box represents the median in each condition and the cross is the mean. The open dots represent the most extreme data points. Cohens d is given for comparison between the thresholds for participants with ASC and NT in each condition.
5.2.2 Multisensory TOJs

Psychometric functions in each condition with data pooled for each group are displayed in Figure 5.6.

![Psychometric functions](image)

**Figure 5.6** Psychometric functions with data pooled within each group. The data points for the ASC group are represented by blue plus signs and their fitted curve is represented by the unbroken line, the NT group are represented by the circles and their fitted curves are the broken lines. Greater multisensory temporal acuity is given by a steeper Psychometric function. Note that individual fitted functions were used to calculate the JNDS and PSEs used in the analysis as functions fitted at the group level lack the sensitivity to detect individual differences in performance.

**Just Noticeable Difference**

JND data is displayed in Figure 5.7. Across the groups JNDS were lowest in the tactile-auditory condition and largest in the auditory-visual condition, with visual-tactile JNDS falling in between. A mixed ANOVA [Condition (Auditory-Visual, Visual-Tactile, Tactile-Auditory) x Group (ASC, NT)] revealed a significant effect of condition ($F(2, 68) = 6.46, p = .003, \eta_p^2 = .160$) indicating that the size of the JNDS differed between the conditions. To follow up the significant effect of condition, data was pooled between the groups and paired sample t-tests (Bonferroni corrected, $\alpha = .017$) were conducted to compare the JND between each condition. The JND in the auditory-visual condition was significantly larger than the tactile-auditory condition ($t(35) = 3.24, p = .003, d = .53$) and the visual-tactile condition ($t(35) = 2.95, p = .006, d = .45$). The JND in the visual-tactile was larger than the tactile-auditory condition, but this difference did not reach statistical significance ($t(35) = .51, p = .612, d = .10$).
There were two critical tests for differences in multisensory temporal sensitivity between the groups. First, there was no main effect of group (F (1, 34) = .096, \( p = .758, \eta_p^2 < .01 \)), indicating that the size of the JNDs were similar for participants with ASC and NT. Second, the condition x group interaction did not reach significance (F (2, 68) = 2.14, \( p = .126, \eta_p^2 = .059 \)) indicating participants with ASC and NT produced statistically comparable JNDs across each condition.

![Figure 5.7 JND (ms) in each multisensory pairing for participants with ASC (blue) and NT (red). The edges of each box represent the upper and lower quartile and the whiskers represent the most extreme deciles. The line within the box represents the median in each condition and the cross the mean. The open dots represent the most extreme data points. Cohens d is given for comparison between SD for participants with ASC and NT in each condition.](image)

Multiple regressions were calculated for each group to explore the relationship between each participant’s self-reported sensory score using the GSQ and the JNDs for each bimodal pairing. JNDs did not significantly predict sensory traits for the ASC (F (3, 15) = 1.47, \( p = .273 \)), or NT group (F (3, 17) = .17, \( p = .916 \)). A summary of the regression data is included in Table 5.2.
**Table 5.2 Regression data comparing multisensory temporal sensitivity and sensory traits**

<table>
<thead>
<tr>
<th></th>
<th>$R^2_{\text{adjusted}}$</th>
<th>$\beta$</th>
<th>$t$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auditory-Visual JND</td>
<td>.09</td>
<td>.46</td>
<td>1.11</td>
<td>.289</td>
</tr>
<tr>
<td>Visual- Tactile JND</td>
<td>.32</td>
<td>1.89</td>
<td></td>
<td>.083</td>
</tr>
<tr>
<td>Tactile- Auditory JND</td>
<td>.65</td>
<td>1.04</td>
<td></td>
<td>.320</td>
</tr>
<tr>
<td>NT</td>
<td></td>
<td>.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auditory- Visual JND</td>
<td>.08</td>
<td>.23</td>
<td></td>
<td>.824</td>
</tr>
<tr>
<td>Visual- Tactile JND</td>
<td>.10</td>
<td>.35</td>
<td></td>
<td>.730</td>
</tr>
<tr>
<td>Tactile-Auditory JND</td>
<td>.06</td>
<td>.19</td>
<td></td>
<td>.853</td>
</tr>
</tbody>
</table>

**Point of Subjective Equality**

The PSEs were statistically comparable across conditions and appeared close to 0 suggesting no bias in the judgements. There were no between group differences in PSEs (see Figure 5.8). For the ASC group, self-reported sensory traits were well predicted by the PSE in the auditory-visual condition (Figure 5.9).

A mixed ANOVA [Condition (Auditory-Visual, Visual-Tactile, Tactile-Auditory) x Group (ASC, NT)] revealed no main effect of condition ($F (2, 68) = 1.88, p = .161, \eta^2_p = .052$) indicating that the PSE did not significantly differ between the conditions. There was no main effect of group ($F (1, 34) = 1.78, p = .192, \eta^2_p = .05$) or condition x group interaction ($F (2, 68) = .08, p = .920, \eta^2_p = .002$).

![Figure 5.8 PSE measured in each condition for participants with ASC and NT. The line within each box represents the median in each condition and the cross the mean. The edges of the box represent the upper and lower quartile and the whiskers represent the most extreme deciles. The open dots represent the most extreme data points. Positive values of auditory-visual pairings (AV) indicate that the beep preceded the flash, visual-](image-url)
tactile (VT) that the flash preceded the vibration and tactile-auditory (TA) that the vibration preceded the beep.

One sample t-tests (Bonferroni corrected, $\alpha = .017$) were conducted to compare the PSE with objective simultaneity for each group independently. There were no significant differences from 0 for the participants with ASC ($t < 2.34$, $p > .032$), or NT ($t < 1.04$, $p > .031$).

Multiple regressions were calculated for each group to explore the relationship between each participant’s self-reported sensory score using the GSQ and the PSE for each bimodal pairing. The regression model revealed that PSE scores overall did not significantly predict sensory traits for participants with ASC ($F (3, 15) = 2.61$, $p = .100$), or NT ($F (3, 17) = .83$, $p = .498$). A summary of the regression data is included in Table 5.3.

Table 5.3 Regression data comparing PSE in each condition with total sensory scores. Predictors of sensory scores are highlighted with an asterisk.

<table>
<thead>
<tr>
<th>Group</th>
<th>R$_{adj}^2$</th>
<th>$\beta$</th>
<th>$t$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASC</td>
<td>.24</td>
<td>Auditory-Visual PSE</td>
<td>.61</td>
<td>2.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Visual- Tactile PSE</td>
<td>.02</td>
<td>.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tactile-Auditory PSE</td>
<td>.03</td>
<td>.12</td>
</tr>
<tr>
<td>NT</td>
<td>.03</td>
<td>Auditory- Visual PSE</td>
<td>.25</td>
<td>.66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Visual- Tactile PSE</td>
<td>.27</td>
<td>.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tactile- Auditory PSE</td>
<td>.26</td>
<td>.91</td>
</tr>
</tbody>
</table>

For the participants with ASC auditory-visual PSEs were predicted by total sensory score (Figure 5.9).

Figure 5.9 PSE data in the auditory-visual condition plotted as a function of total sensory score for participants with ASC.
5.3. Discussion

5.3.1 Summary
The aim of Experiment 6 was to explore the temporal acuity of multisensory information in adults with ASC. JNDs did not differ between the groups for any bimodal pairings. Unisensory temporal acuity thresholds were also statistically comparable between the groups. For both the unisensory and bimodal tasks, variability in performance in the ASC group was increased. For the ASC group, participants producing shifts in the auditory-visual PSE towards audition reported increased sensory traits.

5.3.2 Unisensory temporal acuity
Thresholds were lowest for auditory judgements, followed by tactile and visual. This is in agreement with previous studies of unisensory temporal processing (Humes, Busey, Craig & Kewley-Port, 2010; Jones, Poliakoff & Wells, 2009; Kanabus, Szelag, Rojek & Pöppel, 2002; Kwakye et al., 2011). In the present study, thresholds were not statistically distinguishable between the groups. The few previous studies which have investigated temporal processing in ASC to date have yielded mixed findings. Adults with ASC have previously been observed to produce superior simultaneity judgments of visual bars presented either side of a central fixation point (Falter, Elliott, & Bailey, 2012). However, a study which included auditory TOJs to stimuli presented to either ear revealed reduced temporal acuity in comparison to controls (Kwakye et al., 2011).

Furthermore, as has been described in section 4.5, adults with ASC produced increased TOJ thresholds when stimuli were presented to different fingers on the same hand (Tommerdahl et al., 2008). All of these experiments involved participants making temporal judgements about stimuli presented from separate spatial locations whereby the location of the stimuli may provide an additional cue regarding temporal order. In the present experiment, stimuli were presented from a single location and required no spatial judgement. It may be that basic temporal processing of unisensory information is intact in adults with ASC, but the interaction between space and time may be affected in some way. However, it is worth noting that there was considerable variability in thresholds in the ASC group. Although between group comparison did not reach statistical significance there was a moderate effect of participants with ASC producing larger visual \( (d = .64) \) and tactile thresholds \( (d = .84) \).

5.3.3 Multisensory performance
JNDs were largest in the auditory-visual condition, followed by visual-tactile and tactile-auditory. This is consistent with previous findings from crossmodal TOJ tasks and the...
JNDs produced by participants are comparable (Spence et al., 2003; Zampini et al., 2005), although auditory-visual JNDs (100ms) were somewhat higher than previously reported (e.g. 42ms reported in Spence et al., 2003). In the present study, TOJs for each bimodal pairing were interleaved meaning that the participants were required to switch attention between different modalities (Driver & Spence, 1998; Spence, Nicholls, & Driver, 2001). This may have increased the demands of the task and had some effect on temporal acuity.

JNDs did not statistically differ between the groups in the present experiment suggesting crossmodal temporal sensitivity is typical in ASC. This is in agreement with the findings of Experiment 4 which revealed that visual-tactile information is temporally modulated in ASC and can also be observed here in a task which involved explicit temporal judgements. This differs from previous studies which have suggested that temporal sensitivity is reduced for simple auditory-visual stimuli in children and young adults with ASC (de Boer-Schellekens, Eussen, et al., 2013; Stevenson, Siemann, Schneider, et al., 2014), but agrees with recent research in which adults with ASC produced typical auditory-visual temporal performance (de Boer-Schellekens, Keetels, et al., 2013). As audio-visual temporal sensitivity is believed to be reduced in ASC, it is interesting that the effect size was smallest (d = .01) for the comparison between auditory-visual JNDs in the present study. However, similar to the unisensory thresholds, there was some variability in the ASC participant’s performance. For example, the most extreme values for auditory-visual JNDs (Figure 5.7) display a participant close to 0 and another over 200ms.

In the present experiment, PSEs did not differ significantly between the conditions and were comparable to objective simultaneity. A number of previous studies in NT individuals have produced PSEs that differ from objective simultaneity (e.g. Spence et al., 2003; Zampini et al., 2005). However, there is considerable variability in PSEs between experiments and the difference from previous studies may simply reflect individual and/or stimulus differences (Boenke et al., 2009; Spence, Shore, et al., 2001; Stone et al., 2001). Previous studies have indicated that PSEs vary between individuals and can be influenced by attention to a particular modality, and the stimulus duration and intensity. The relationship between auditory-visual PSEs and self-reported sensory traits is a novel finding. Participants with ASC who required a greater auditory lead to perceive the stimuli as simultaneous reported more sensory traits. Counterintuitively, this auditory lead likely reflects a visual bias as vision first responses must be produced...
on a greater proportion of trials to shift the PSE in this direction. The finding that a visual bias predicted sensory traits in our ASC sample is somewhat consistent with an auditory-visual SJ task in NTs which indicated that a shift in PSEs towards auditory stimuli was well correlated with autistic traits (Donohue, Darling, & Mitroff, 2012). A recent study which compared neural activity in NTs during auditory-visual TOJ and SJ tasks indicated that a number of prefrontal and parietal regions are uniquely activated during TOJ tasks (Binder, 2015). The authors propose that TOJ tasks may involve a number of higher order processes in addition to temporal discrimination, including the selective attention to vision. Bias on crossmodal TOJ tasks may suggest at differences in selectively attending to a particular sense in ASC which warrants further investigation. Alternatively, previous research in NTs has suggested that the PSE can be biased towards a more salient stimulus in a pairing, as that stimulus will capture attention and be processed more quickly (Spence & Parise, 2010). This may be related to enhanced perceptual processing of certain stimuli in some individuals with ASC (see Mottron & Burack, 2001), contributing to everyday sensory issues.

The findings of Experiment 6 provided no evidence for atypical temporal sensitivity to multisensory information in adults with ASC. As multisensory temporal sensitivity typically matures across development (Hillock et al., 2011; Hillock-Dunn & Wallace, 2012), it may be that there is a developmental delay in this maturation in individuals with ASC leading to reduced temporal acuity in children and adolescence. By adulthood, multisensory temporal sensitivity may have ‘caught up’ with NT performance. However, the variability in the ASC data suggests that there are important individual differences in temporal processing of crossmodal stimuli. Indeed, PSE data revealed that the ASC participants who processed visual information more quickly for auditory-visual judgements reported more sensory symptoms. Future work should seek to further characterise these individual differences in multisensory temporal processing in ASC.
Chapter 6
Exploring the spatial modulation of visual-tactile interactions in adults with autism spectrum conditions
‘I still can’t even tell when I’ve stepped on someone’s foot or jostled someone out of my way. So something connected with my sense of touch might be mis-wired too’

Naoki Higashida, a boy with ASC (Higashida, 2013, The Reason I Jump, pg16)

6.1. Introduction
In Experiment 5, both participants with ASC and NT produced multisensory interactions for visual-tactile stimuli presented in the same spatial location. However, unlike NT participants those with ASC also produced this effect when the visual distractor was presented 42cm from the tactile target in the opposite hemispace (see Chapter 4). This suggests that the spatial modulation of visual-tactile interactions may be affected in individuals with ASC. We consider three possible accounts of this finding that are explored in Experiments 7 to 9. First, the representation of peripersonal space may be extended in participants with ASC. To explore this possibility an alternative visual-tactile task with a spatial manipulation was used in Experiment 7. Second, the fact that participants were required to inhibit attention to distractors presented in multiple locations in Experiment 5 may have been more difficult for people with ASC than NT participants, leading to an increased influence of the distant distractor. Therefore, we sought to replicate the effect using a version of the CCT with fewer distractor locations in Experiment 8. Finally, participants with ASC may have a more general issue with selective attention which is not specifically multisensory. To explore this possibility, participants completed a visual only selective attention task, similar to the CCT, in Experiment 9. This chapter first introduces peripersonal space and selective attention in more detail, before describing tasks chosen to investigate these three hypotheses.

6.1.1. Peripersonal space
Peripersonal space refers to the multisensory representation of the area immediately surrounding the body, which has a distinct neuronal representation from extrapersonal space which is beyond reach (Rizzolatti et al, 1997). Studies in non-human primates have revealed that separate populations of neurons are preferentially activated in response to visual stimuli presented in either this peripersonal, or in extrapersonal space (Cléry, Guipponi, Wardak & Ben Hamed, 2015; Meredith & Stein, 1986). Subsequent visual-tactile and audio-tactile behavioural tasks in humans have indicated that multisensory interactions are increased when the stimulus is located proximal to the participant’s body (e.g. Kitagawa, Zampini, & Spence, 2005; Lloyd, 2007). The representation of multisensory peripersonal space can be modulated by social interaction (Maister, Cardini, Zamariola, Serino, & Tsakiris, 2015; Teneggi, Canzoneri, di Pellegrino, & Serino, 2013), and emotions such as fear and anxiety (Sambo & Iannetti, 2013; Taffou & Viaud-Delmon, 2014).
To date, Experiment 5 is the only study to characterise the spatial modulation of visual-tactile interactions in ASC, which can provide a proxy measure of peripersonal space. There are two previous studies which have investigated the representation of social peripersonal space in ASC explicitly. Parental questionnaires have previously revealed that children with ASC have an increased propensity to invade personal space in comparison to NT siblings (Kennedy & Adolphs, 2014). In contrast, when children with ASC and NT were asked to interact with an experimenter, the ASC participants reported feeling more comfortable when the experimenter was at a greater distance in comparison to NT children (Gessaroli, Santelli, di Pellegrino, & Frassinetti, 2013). There is clearly a need to further explore the representation of space in ASC and one approach is to utilise experiments exploring the low-level representation of peripersonal space. If low-level representations of peripersonal space are affected in ASC this may impact on higher level social behaviours. To provide converging evidence for the findings of Experiment 5, an alternative spatial visual-tactile task was used in Experiment 7.

A visual-tactile TOJ including a spatial manipulation was utilised in Experiment 7. A number of studies have previously indicated that performance on visual-tactile TOJs are improved when the visual stimulus is presented beyond the individual’s representation of peripersonal space. Spence et al. (2003) explored visual-tactile TOJs in NT participants; bimanual tactile stimuli were presented 52cm apart either side of the body midline, with visual stimuli directly in front of the tactile. The stimuli were presented in either the same location (visual-tactile stimuli in the same hemispace), or in different locations (visual-tactile stimuli appeared either side of the midline). JNDs were significantly reduced when the tactile stimulator and light were separated (near condition, JND = 45ms; far condition, JND = 28ms). Similarly, this benefit of spatial discrepancy on multisensory TOJs has also been observed for visual-auditory pairings when stimuli are separated across the body midline (Keetels & Vroomen, 2005; Zampini, Shore, & Spence, 2003a, Zampini, Shore, & Spence, 2003b), and for audio-tactile pairings where the auditory stimulus is presented behind the participant’s head (Kitagawa et al., 2005; Zampini, Brown, et al., 2005).

This spatial redundancy effect (Spence et al., 2003) for visual-tactile TOJs is used as a proxy measure of peripersonal space in Experiment 7. This task provides a behavioural measure of visual-tactile interactions in near and far space. Visual-tactile stimuli which are presented beyond a participant’s representation of peripersonal space are less likely to interact at shorter SOA than when within a participant’s representation of peripersonal space. Comparing the spatial redundancy effect between participants with
ASC and NT thus provides an indirect measure of peripersonal space. This is discussed further in section 6.2.

6.1.3. Selective attention
An alternative explanation for the findings of Experiment 5 is that individuals with ASC have an issue with selective attention. That is, some issue with selectively attending to the target made the distant distractor more difficult to suppress. Selective attention involves increasing the processing of relevant information, while inhibiting extraneous, potentially distracting information (see Parasuraman & Davies, 1984). The flanker task (Eriksen & Eriksen, 1974) is a frequently used paradigm to investigate the inhibition of distractor interference. Participants are asked to respond to a target stimulus as quickly as possible. Simultaneous distracting information flanks the target, which may be either incongruent or congruent with the correct response. RTs are typically increased in incongruent trials over congruent trials and the size of this effect is a measure of inhibition. The flanker effect can be reduced if the participant is primed to expect more incongruent than congruent distractors, suggesting that inhibition can be modulated by distractor predictability (Lehle & Hübner, 2008; Wendt, Kluwe, & Vietze, 2008). Similarly, there is evidence that the extent to which distractors are inhibited varies as a function of spatial predictability (Munneke, Van der Stigchel, & Theeuwes, 2008); distractors which appeared in an unpredictable location had a stronger effect than when the location of the distractor was cued beforehand. Additional attentional resources may be required when distractors appear in unpredictable locations. In Experiment 5, distractors were presented unpredictably from four spatial locations simultaneously with the target. It may be that this increased the attentional demand of processing the tactile stimulus, increasing the task difficulty and influencing the perception of the target. The apparent reduced spatial modulation observed in the ASC group may have been brought about by these additional task demands rather than issues with modulating the distractor.

Alternatively, the effects observed in Experiment 5 may have been the result of a more general difficulty with selectively attending to a target and inhibiting irrelevant distractors in ASC. There is a substantial literature investigating aspects of attention in ASC (for a detailed review see Ames & Fletcher-Watson, 2010), and there is evidence that selective attention may be affected, relating to executive functioning deficits (Hill, 2004; Ozonoff, Pennington, & Rogers, 1991; Robinson, Goddard, Dritschel, Wisley, & Howlin, 2009). Participants with ASC exhibit an increased effect of distractors on tasks which require the identification of a target surrounded by distractors in comparison to
NT controls. For example, children with ASC produce increased RTs on incongruent trials in variants of the flanker task (Adams & Jarrold, 2012; Christ, Holt, White, & Green, 2007; Christ, Kester, Bodner, & Miles, 2011). Participants with ASC also produced more response inhibition errors on an anti-saccade task where the participant is instructed to volitionally direct their gaze, and attention, in the opposite direction to a peripheral distractor (Luna, Doll, Hegedus, Minshew, & Sweeney, 2007). The increased interference effect of a distant distractor observed in Experiment 5 is consistent with the suggestion that individuals with ASC have difficulties filtering spatially disparate distracting information (Burack, 1994). Typically, distractors only influence performance when presented in a position of relative proximity to the target and may be filtered out if presented further away. Children with ASC with an IQ in the learning disabled range showed an increased effect of distractors that were presented in distant positions (up to ~10cm from the target) in comparison with age and IQ matched controls. The presence of a grey window which separated the distant distractors and the target improved filtering in the control group. However, the window did not ameliorate distractor effects in participants with ASC. In contrast, other findings have suggested that individuals with ASC may have an overly focussed area of visual attention (Robertson, Kravitz, Freyberg, Baron-Cohen, & Baker, 2013). Participants indicated the orientation of a gap in a circle which was presented at their contrast threshold. Both groups produced improved performance when a cue was presented close to the target prior to presentation. Performance diminished when the cue was spatially separated from the target circle. Participants with ASC showed a pronounced reduction in performance with spatial disparity which the authors attributed to an over-focussing of spatial attention. Over-focussed attention in ASC has also been suggested as a possible explanation for increased thresholds on coherent visual motion processing tasks (Ronconi et al., 2012).

Despite considerable interest in selective attention in ASC, there have been relatively few studies investigating selective attention across the sensory modalities. It has been well established in the NT literature that attention can be directed across the sensory modalities both exogenously (automatically) and endogenously (consciously), in a similar manner to effects observed in classic studies of selective attention. Endogenous shifts in attention are typically measured in paradigms in which the participant is asked to attend to a particular modality explicitly by the experimenter, or presenting the participant with a prior cue alerting them to the modality to be attended (e.g. Lukas, Philipp, & Koch, 2014; Spence & Driver, 1997b). Exogenous shifts between the modalities can be observed following non predictive cues in a particular modality, or
through the effects of the modality of a prior target (e.g. Miles, Brown, & Poliakoff, 2011; Rodway, 2005; Turatto, Benso, Galfano, & Umiltà, 2002). There is evidence that endogenous shifts in attention between audition and vision are slower in children with ASC in comparison to controls (Courchesne et al., 1994). A recent study of exogenous attention has indicated that inhibition of information across the senses is reduced in ASC (Murphy, Foxe, Peters, & Molholm, 2014). Children with ASC performed a detection task in which a cue primed the participant to respond to threshold stimuli in a particular modality (either vision or audition). The ASC group showed reduced sensitivity and increased RTs when a task irrelevant tone was presented with a visual stimulus, an effect that was not observed in the NT children. Furthermore, ERPs revealed that task based modulation of alpha band activity, which is believed to reflect the suppression of irrelevant sensory information, was markedly reduced in the ASC group.

The studies described above indicate that NT individuals can preferentially process information from different sensory modalities both automatically and consciously. Further to this there is substantial evidence that there are links in spatial selective attention across the senses in NTs. For instance, attention to a target in a particular modality will typically direct attention in other modalities to the same location as the target, while spatially discrepant information in another modality will be inhibited (Lloyd, Merat, McGlone, & Spence, 2003; Spence & Driver, 1997a; Spence, Pavani, & Driver, 2004). The results of Experiment 5 may reflect that multisensory attention to a target location is reduced in ASC as spatially discrepant visual information had a greater effect on tactile processing than in NTs. In Experiment 8 we sought to replicate the finding of reduced suppression of spatially discrepant distracting information in ASC, and to explore whether this effect can also be observed within the visual modality in Experiment 9.

To summarise, reduced spatial modulation of visual-tactile stimuli was observed in participants with ASC in Experiment 5. There are a number of possible accounts for this finding. Firstly, participants with ASC may have an extended representation of peripersonal space meaning that the far distractor was interacting with the tactile stimuli. This is investigated using an alternative visual-tactile task in Experiment 7. Second, it may have been that presenting lights from multiple locations created increased attentional demands which disproportionately affected the participants with ASD. To discount this possibility, the CCT was repeated using fewer distractor locations in Experiment 8. Third, if reduced multisensory selective attention in ASC was replicated
in Experiment 8, a remaining question is whether this effect is specifically multisensory or can also be observed in the visual modality. This possibility is explored in Experiment 9 in which a visual only version of the CCT was developed.

6.2. Experiment 7 Introduction
In Experiment 7, participants made TOJs to visual-tactile stimuli presented in either the same location or the contralateral hemispace. At the beginning of each block, participants were instructed that the visual stimuli would be presented near to their hand (0cm from tactor), or in the position far from their hand (42cm from the tactor in the opposite hemispace). Stimuli were blocked in this way to avoid the need to divide attention between spatial locations (See Driver & Spence, 1998). Dividing attention between the locations could have a deleterious effect on participants with ASC and cloud the measurement of TOJs.

If the visual stimulus is presented at a shorter SOA, within a participant’s peripersonal space the stimuli are more likely to be perceptually bound (Stein & Stanford, 2008). If multisensory stimuli are perceptually bound, they will be more difficult to separate in time, leading to diminished TOJ performance. Increasing the spatial disparity between the stimuli reduces the likelihood of multisensory stimuli interacting, leading to an improvement in the participant’s sensitivity to the detection of temporal order. The participant can use redundant spatial information when crossmodal stimuli are presented either side of the body midline to help discern the stimulus order, leading to improved precision over conditions where the stimuli are presented in the same location. We predicted that NT participants would show an improvement in TOJs when the stimuli were spatially separated, which would be observed by significantly reduced JNDs in the far location in comparison to the near. If individuals with ASC have a representation of peripersonal space which is extended into the contralateral hemispace, then stimuli positioned in this location would be perceptually bound at shorter SOAs. This would likely lead to a reduced benefit of spatial discrepancy when making visual-tactile TOJs in Experiment 7. Furthermore, PSEs were compared to 0 to explore any bias in the visual-tactile estimate for each condition, although no effects were anticipated. Finally, the relationship between questionnaire measures from the AQ and GSQ were correlated with performance on these tasks to explore any relationships between bias and sensitivity with autistic and sensory traits.
6.3. Experiment 7 Method

6.3.1. Apparatus
Participants sat at a desk in a dimly lit room and were instructed to focus on a central fixation point, consisting of a white cross (19 mm) on a computer monitor, displayed approximately 30° below eye level and approximately 45 cm from the participant.

Participants held a 70 mm foam cube between the thumb and forefinger of their dominant hand into which was embedded a bone conductor (Oticon Limited, B/C 2-PIN, 100Ω, Hamilton, UK) which was driven by sound files (sine wave, 440Hz, 0.8 AMPs) from a PC through a Tacamp amplifier (Dancer Design, St. Helens UK). The participant’s index finger was attached to the bone conductor with double-sided adhesive tape. A black cardboard shield surrounded the monitor and was embedded into the foam cube, concealing the participant’s index finger from view. A 10mm LED positioned directly above the bone conductor was visible through a 10mm hole in the shield (the ‘near’ condition). This created the impression that the light was emitted from the tip of the participant’s finger (see Figure 6.1). An identical LED was visible through the shield in the contralateral hemispace, 42cm from the participant’s stimulated hand (the ‘far’ condition). Each LED was positioned 26.5cm from the central fixation point.

![Figure 6.1 Schematic of the experimental set-up for a right handed participant. The bone conductor was positioned behind the cardboard shield and appeared in the same location as the near LED. The far LED was positioned 42cm from the target in the opposite hemispace.](image)

White noise (~75dB SPL) was played through headphones throughout the experiment to prevent the participant from hearing sounds emitted by the bone conductor.
6.3.2. Stimuli and Design
Stimuli were presented at ± 20ms, 55ms, 90ms, 200ms and 400ms stimulus onset asynchronies (SOA) where negative SOAs indicate that the visual stimulus preceded the tactile stimulus. Participants were presented with visual stimuli at each SOA in one of 2 conditions: near (equivalent to the 0cm distractor location in Experiment 5) and far (equivalent to 42cm_opp).

6.3.3. Procedure
On each trial, participants received a 8ms tactile vibration and a 8ms light flash. Participants were required to state whether vision or touch was presented first in each condition. The fixation cross appeared on screen for an interval randomly selected from a uniform distribution ranging between 500-1000ms, remaining on screen as the stimuli were presented. To prevent anticipation errors a 200ms delay was included after the presentation of the stimuli, during which the participant could not respond. After the stimuli were presented an onscreen prompt appeared reading ‘Was the flash or touch first?’ Participants made unspeeded verbal responses, which were recorded by the experimenter. There was a delay of 1000ms after the experimenter entered the participant’s response before the next trial commenced. No feedback was provided during the experimental trials. The 20ms-200ms SOA trials were each presented 20 times and the 400ms SOA 8 times for each condition. Trials were randomly intermixed. Each condition was presented over four blocks of 88 trials, giving 352 trials in total. Participants received alternating blocks of the near and far conditions, with the starting condition counterbalanced between participants.

Prior to beginning the experimental trials participants completed a practice procedure of 10 trials with the light flash presented from the near and far locations at ±400ms SOA. Feedback was provided in the practice trials, incorrect responses were followed by an ‘incorrect’ sign which was displayed on screen for 1000ms. Participants continued to the experimental trials once the task instructions were understood and performance was at least 80% accurate for each condition.

6.3.4. Data analysis
Participant responses in each condition were converted to proportion of ‘vision first’ responses. Each participant’s data for each condition was then fit by a cumulative Gaussian Psychometric function (see Appendix F1). We used mixed ANOVAs with group as the independent factor to explore whether JND and PSE differed between the groups in each condition. Statistically significant interactions were followed up with independent sample t-tests. Single sample t-tests were also used to compare the PSE
with objective simultaneity for each group in each position. The difference between each participant’s JND data in the far and near location was calculated as a measure of the spatial redundancy effect. Pearson’s correlation coefficients were calculated to explore any relationship between this measure and the PSE and with participant’s total sensory score on the GSQ and AQ scores.

6.4. Experiment 7 Results

6.4.1. Just Noticeable Differences
An example Psychometric function is included in Figure 6.2. For both groups, JNDs were significantly lower in the far condition in comparison to the near, indicating a spatial redundancy effect. Group did not interact with position, suggesting the spatial redundancy effect was comparable between the groups (see Figure 6.3).

Figure 6.2 An example psychometric function for a single participant including the near (green circles) and far conditions (magenta crosses). It can be seen that this participant is showing a benefit of spatial discrepancy as the slope in the far condition is steeper than the near condition meaning that the JND is reduced with increased discrepancy.

This was confirmed using a mixed ANOVA [Condition (Near, Far) x Group (ASC, NT)] which revealed a significant effect of condition \( F(1, 34) = 6.10, p = .019, \eta^2_p = .15 \) indicating that the JND was significantly larger in the near than the far condition (near mean = 78.02ms ± 37.25, far mean = 66.31ms ± 40.17). There was no main effect of group \( F(1, 34) = .09, p = .766, \eta^2_p < .01 \), indicating that JNDs were comparable
between the groups. Critically, the condition x group interaction did not reach significance \((F (1, 34) = .03, p = .859, \eta_p^2 < .01)\) indicating that JNDs across the conditions was comparable between the groups.

![Box plot diagram](image)

*Figure 6.3 JND (ms) in the near and far condition for participants with ASC (blue) and NT (red). The line within the box represents the median in each condition and the cross the mean. The edges of the box represent the upper and lower quartile and the whiskers represent the most extreme deciles. The open dots represent the most extreme data points. The difference in mean performance between the near and far conditions gives the spatial redundancy effect for each group.*

### 6.4.2. PSE

The PSE provides a measure of the participant bias towards vision or touch. There were no significant effects or interactions for PSE indicating that the bias in visual-tactile TOJs was similar between the groups and conditions (see Figure 6.4). A mixed ANOVA [Condition (near, far) x Group (ASC, NT)] revealed no significant effect of condition \((F (1, 34) = .225, p = .638, \eta_p^2 = .01)\) indicating that the PSE did not significantly differ between conditions. There was no main effect of group \((F (1, 34) < .01, p = .966, \eta_p^2 < .01)\). The condition x group interaction did not reach statistical significance \((F (1, 34) = .110, p = .742, \eta_p^2 < .01)\).
To investigate any significant bias towards vision or touch in the TOJs one sample t-tests (Bonferroni corrected, $\alpha = .025$) were then conducted to compare the PSE with objective simultaneity for each group independently. Neither the near or far condition were significantly different from 0 for the participants with ASC ($t < 1.24, p > .232$), or NT ($t < 1.34, p > .20$).

### 6.4.3. Relationship with questionnaire data

Pearson’s correlation coefficients (Bonferroni corrected $\alpha = .025$) were then calculated to explore any relationships between total sensory score and the spatial redundancy effect (far-near JND). There were no significant correlations for participants with ASC ($r (17) = .34, p = .162$), or for NT ($r (17) = .16, p = .520$). A Pearson’s correlation coefficient was also calculated to investigate any relationship between autistic traits as measured using the AQ and the size of this spatial redundancy effect in NT participants. There was no significant correlation ($r (15) = .41, p = .119$)

PSE measured in each condition and total sensory scores were also correlated (Bonferroni corrected $\alpha = .025$) to explore any relationship between bias in visual-tactile processing and sensory traits. There were no significant correlations for participants with ASC ($r < .18, p > .480$) or NT ($r < .36, p > .138$). Finally, PSEs in each condition and
AQ scores reported by NT participants were correlated. There were no significant correlations ($r < .36, p > .172$).

### 6.5. Experiment 7 Discussion

In Experiment 7, we sought to explore the representation of peripersonal space in ASC using a visual-tactile task in which participants made TOJs where the visual stimuli was presented in a position either near or far from the participant’s stimulated hand. In line with a number of previous studies, JNDs were reduced when presented in the far condition over the near condition (e.g. Poliakoff, Shore, et al., 2006; Spence et al., 2003). That is, participants showed a benefit of spatial redundancy on visual-tactile TOJs. Critically, there was no difference in performance between the groups meaning that participants with ASC were also able to use redundant spatial cues when making visuotactile TOJs. If the visual stimuli presented in the far location fell within an extended representation of peripersonal space, then stimuli presented at shorter SOA would bind and JNDs would not be reduced. Therefore, it is unlikely that the findings of Experiment 5 were due to an expanded representation of peripersonal space in adults with ASC.

### 6.6. Experiment 8 Introduction

In Experiment 8 we sought to replicate the atypical spatial modulation of visual-tactile stimuli that was reported in Experiment 5. We explored whether the influence of the distant distractor was brought about by difficulties inhibiting visual distractors that were presented unpredictably from several spatial locations, or represented a more specific absence of spatial modulation in ASC. We repeated the spatial CCT reported in Experiment 3 and 5 using only the distractors presented at 0cm (near) and 42cm_opp (far). It is likely that using fewer distractor locations would reduce the attentional demands of the task as the predictability of distractor location would be improved. In Experiment 5, visual distractors were presented simultaneously with the tactile target and appeared unpredictably across four spatial locations. It may be that the significant effect of the distractor in the 42cm_opp condition for the participants with ASC was brought about by these increased task demands.

In Experiment 8, the NT participants were expected to show a significantly increased interference effect in the near condition in comparison to the far as has previously been observed in the typical version of the CCT which utilises only these locations (e.g. Holmes et al., 2006; Spence, Pavani, & Driver, 2004). Following the results of Experiment
5, it was expected that for participants with ASC the interference effect of incongruent distractors would not differ significantly between the near and far condition.

6.7. Experiment 8 Method
See Experiment 5 (section 4.2.3) for full details of the apparatus, stimuli, design and procedure of the CCT. Participants completed a 2IFC adaptive staircase procedure to determine their tactile temporal thresholds. Experimental stimuli were then presented at the participant’s threshold.

6.7.1. Apparatus and Stimuli
Experiment 8 was similar to Experiments 3 and 5, except that the 21cm and 42cm distractors were removed. The only other difference was that the tactor was embedded in a 70mm foam cube positioned behind the cardboard shield rather than a position in front of the shield (see Figure 6.1).

6.7.2. Design and Procedure
An adaptive staircase procedure (PEST; see Taylor & Creelman, 1967) was used to determine the duration required between two vibrations for the participant to correctly identify a double pulse 75% of the time. A break was included after 50 trials and the procedure was capped at 100 trials. If a threshold had not already been determined by the 100th trial the threshold was taken as an average of the step from the 20th trial (ASC n=11; NT n = 7).

There were five conditions: distractors (congruent, incongruent) x position (near and far) plus baseline trials. Each condition was presented ten times in each block, with half of these trials being single vibrations and half double. The experiment consisted of four experimental blocks of 50 trials, giving 200 trials in total.

Before the experimental procedure began, there were two practice blocks to familiarise participants with the task and ensure that the threshold procedure had worked effectively. Participants first completed five trials with the gap duration set at 200ms to ensure that they understood the task instructions. Participants then completed 28 randomly intermixed trials: 20 baseline trials and 8 trials with light flashes, four in each condition with each combination of congruent/ incongruent trials with single/double pulses. If participants did not perform at 75% accuracy ±10% in baseline trials on this block then the gap duration was increased or decreased by 1ms before beginning the experimental procedure (ASC n = 4; NT n = 7). If participants performed at greater than
95%, or below 55%, accuracy then the participant repeated the threshold procedure (ASC n = 1).

6.7.3. Analysis
Performance accuracy was calculated for each participant in each condition. Participants who performed at greater than 95%, or below 55%, baseline accuracy were excluded from analysis (ASC n = 1; NT n = 1). Reaction times longer than 2000ms (ASC 8.31% of all trials; NT 4.94%), or under 150ms (ASC 3.19%, NT 4.94%) were removed from analysis. Multisensory performance in each condition was contrasted with unisensory performance in the baseline condition using paired sample t-tests. An interference effect was calculated by deducting each participant’s error rate in response to incongruent distractors from their baseline error rate. This interference effect was then compared between the near and far condition for each group using within participants t-tests. Pearson’s coefficients were calculated to explore the relationship between spatial modulation (the difference in the interference effect between the near and far condition) and ratings on the GSQ and AQ. RT data (C1) and congruency effect analysis (D2) are included in the Appendices.

6.8. Experiment 8 Results

6.8.1. Tactile thresholds
An independent samples t-test revealed that there was no significant difference in tactile thresholds between the groups (t (33) = .270, p = .789, d = .09). ASC mean = 21.96ms ± 11.06; NT mean = 23.10ms ± 13.74.

6.8.2. Distractor effects
An independent samples t-test revealed that baseline error rate did not significantly differ between the groups (t (30) = 1.28, p = .209, d = .43). NT participants showed spatial modulation of visual interference on a tactile judgement. Interference effects were reduced between the near and far conditions. NT participants produced an error rate that was significantly (Bonferronni corrected α = .013) greater than baseline for incongruent distractors presented in the near condition (t (15) = 3.04, p = .008, d = .88). No other differences reached statistical significance (t < 2.03, p > .060). Spatial modulation was reduced in the ASC group (see Figure 6.5). Participants with ASC produced an error rate significantly greater than baseline for incongruent distractors presented in the near condition (t (15) = 3.78, p = .002, d = .89), and the far condition (t (15) = 2.84, p = .012, d = .66). There were no other significant differences (t < .172, p > .105).
Figure 6.5 Mean error rate for congruent (diamonds) and incongruent trials (squares) in each position for ASC and NT participants. Mean error rate in the unisensory baseline condition is represented for each group by the dotted line. Asterisks denote a significant difference from baseline (Bonferroni corrected, $\alpha=.013$). Within participants 95% confidence intervals (Cousineau, 2005) are represented in each distractor condition by error bars and in the Baseline condition by the dotted line.

Paired sample t-tests (Bonferroni corrected $\alpha = .025$) were conducted to compare the interference effect at the near and far position within the groups. There was a trend for the interference effect being larger in the near condition than the far for NT participants ($t (16) = 2.43, p = .027, d = .55$), but this effect did not reach statistical significance for participants with ASC ($t (15) = 1.41, p = .179, d = .20$).

### 6.8.3. Relationship with questionnaire data
Pearson’s correlation coefficients (Bonferroni corrected $\alpha = .025$) were calculated to investigate any relationship between total sensory score on the GSQ and the spatial modulation index (near interference effect – far). There was no significant correlation for participants with ASC ($r = -.02, p = .939$), nor NT ($r = .08, p = .775$). For NT participants, the index of spatial modulation was not significantly correlated with AQ score ($r = .27, p = .317$).
6.9. Experiment 8 Discussion

In Experiment 8 we explored the possibility that presenting distractors from multiple locations created high attentional demands, leading to reduced spatial modulation of the distractors in participants with ASC. The adapted CCT was repeated using fewer distractor locations. In Experiment 8, both participants with ASC and NT produced a significantly increased error rate over baseline to distractors presented close to their hand. The participants with ASC also produced this interference effect when the distractor was presented in the distant location. Moreover, the NT group showed a trend towards a reduction in the interference effect from the near location to the far which was not observed in the ASC group. The effects of Experiment 5 were replicated using fewer distractor locations. Therefore, we conclude that the atypical effect of distant visual distractors on a tactile target in ASC is unlikely to be due to high attentional demands as the effect was also observed with fewer distractor locations.

6.10. Experiment 9 Introduction

In Experiment 9, we utilised a purely visual version of our adapted, spatial CCT to explore the possibility that the findings in Experiment 5 and 8 were the result of a general issue in inhibiting distractors at distant spatial locations that was not specific to crossmodal stimuli. This visual congruency task (VCT) was developed and piloted in Appendix F3. It was anticipated that a visual distractor positioned close to the visual target would produce interference effects, but that these interference effects would be reduced in the far condition for NT participants. If our findings from Experiments 5 and 8 were due to a general issue with selective attention in ASC then it would be expected that participants with ASC would produce no reduction in interference effects between the near and far location. If the effects were due to a specific issue with selective attention to touch when presented with visual stimuli, then it would be expected that participants with ASC would show a similar reduction in the interference effect between the near and far locations to controls.

6.11. Experiment 9 Method

6.11.1. Apparatus

Participants sat at a desk in a dimly lit room and were instructed to focus on a central fixation point, consisting of a white cross (19 mm) on a computer monitor, displayed approximately 30° below eye level and approximately 45 cm from the participant.

Participants were instructed to keep the index finger of their dominant hand in a groove in a 70 mm foam cube which was positioned behind the cardboard shield which
surrounded the monitor. It was anticipated that positioning the hand in the same area of space as Experiment 8 would direct the participant’s attention to the target in an equivalent manner (see Spence & Driver, 2004). The apparatus was similar to Experiment 3, 5 and 8. The bone conductor was removed and a 10mm green LED was included (the target). The target was positioned directly below the 0cm distractor. This green LED was covered by a plastic filter to approximately match the luminance (~197 cd/m²) to the red distractor LEDs (~153 cd/m²). The target light could be positioned in a symmetrical location in the contralateral hemispace allowing identical positioning for left handed participants. See Figure 6.6.

Figure 6.6 Schematic of the experimental set up for a right handed participant. Participants were instructed to keep their dominant hand in a position next to the target light behind the cardboard shield. Both distracting LEDs were 27cm from the central fixation point.

6.11.2. Procedure
The procedure was similar to the spatial version of the CCT (Experiments 3, 5 and 8). Participants made judgements about a green visual target that was presented at their approximate threshold level. Red visual distractors were included in a position close to the target (near) and in a position in the contralateral hemispace (far).

Threshold Procedure
Participants received two successive visual stimuli in a 2AFC procedure. The visual stimuli were delivered through the green (target) LED. Stimuli comprised a single visual flash or two 80ms flashes separated by a gap of 0-200ms. The order of presentation was randomised and the overall duration of single and double stimuli was matched. The participant was instructed to indicate which interval contained the double flash using the footpedal. An adaptive staircase procedure (PEST; see Taylor & Creelman, 1967)
was used to determine the duration required between two vibrations for the participant to correctly identify a double flash 75% of the time. A break was included after 50 trials and the procedure was capped at 100 trials. If a threshold had not already been determined by the 100th trial the threshold was taken as an average of the step from the 20th trial (ASC n = 10; NT n = 11).

**Experimental Procedure**

Participants were asked to make speeded responses upon the presentation of a target flash, responding by lifting their toe in response to single flashes, and heel in response to double. Throughout the experimental procedure, flashes were presented at the previously determined approximate threshold level for that participant. The task included both baseline trials and trials with task-irrelevant distracting light flashes delivered from the red LEDs, which were either congruent (e.g. single target flash, single distractor flash) or incongruent (e.g. single target flash, double distractor flash). For single flashes the LED was illuminated for 80ms, double flashes comprised two single 80ms flashes separated by 120ms. Participants were explicitly instructed to ignore the distractor flashes as much as possible.

Distractor and baseline (target only) trials were intermixed. The distractors were presented simultaneously with the target. There were 5 conditions: distractors (congruent, incongruent) x position (near, far) plus baseline trials. There were four experimental blocks of 50 trials, in which each condition was presented 10 times in a randomised order, with half of these trials being single flashes and half double. This gave a total of 200 trials, with 40 trials in each condition.

**Practice Procedure**

Before beginning the experimental procedure, participants completed a practice procedure to familiarise themselves with the task. Participants first completed 5 trials with the duration of gap set at 200ms to ensure that they understood the task instructions. The second practice block featured 28 trials presented at the participant’s threshold level; 20 baseline trials and eight trials including distractors four in each condition with each combination of congruent/ incongruent trials with single/double flashes. If participants did not perform at 75% accuracy ±10% in baseline trials on this block then the gap duration was increased or decreased by 1ms before beginning the experimental procedure (ASC, n = 5; NT, n = 4). As this Experiment was part of a lengthy testing session a more liberal protocol was adopted than Experiments 3 and 5. If performance was 100%, or below 50% accuracy then the participant repeated the threshold procedure (ASC, n = 2; NT, n = 1).
6.11.3. Analysis
Performance accuracy was calculated for each participant in each condition. Participants who performed at greater than 95%, or below 55% baseline accuracy were excluded from analysis (ASC, n = 1; NT n = 1). Reaction times longer than 2000ms (ASC 4.27% of trials, NT 3.25%), or under 150ms (ASC, n = 1.53%; NT, n = 3.18%) were removed from analysis. The same statistical analysis was used as in Experiment 8. Congruency effect analysis is included in Appendix D2 and RT data in Appendix C1.

6.12. Results

6.12.1. Visual thresholds
There was no significant difference in visual thresholds between the groups. This was confirmed using an independent samples t-test (t (32) = .908, p = .371, d = .55). ASC mean = 32.83 ± 41.57, NT mean = 17.84 ± 11.44.

6.12.2. Distractor effects
An independent samples t-test revealed that baseline error rate did not significantly differ between the groups (t (29) = .30, p = .770, d = .11). If participants were spatially modulating the distractors the interference effect would be reduced between the near and far locations. The effect of the distractors was modulated by spatial location in both groups (see Figure 6.7). Participants with ASC produced an error rate significantly greater (Bonferroni corrected α = .013) than baseline for incongruent distractors presented in the near condition (t (14) = 5.35, p < .001, d = 1.56). The congruent distractors produced a significantly reduced error rate in comparison to baseline when presented in the far condition (t (14) = 4.25, p = .001, d = 1.15). No other differences were statistically significant (t < .264, p > .019). NT participants produced an error rate that was significantly greater than baseline for incongruent distractors presented in the near condition (t (15) = 7.20, p < .001, d = 1.97) and the far condition (t (14) = 4.87, p < .001, d = .80). No other differences reached statistical significance (t < 2.40, p > .030).
Paired sample t-tests (Bonferroni corrected $\alpha = .025$) were conducted comparing the interference effect for the near and far condition within groups. Both the ASC ($t (14) = 3.91, p = .002, d = .90$) and NT groups ($t (15) = 2.50, p = .024, d = .85$) produced a significantly greater interference effect in the near condition in comparison to the far.

**6.12.3. Relationship with questionnaire data**

Pearson’s correlation coefficients were calculated to explore any relationship between participants rating on the GSQ and the index of spatial modulation (near interference effect – far). There was no significant relationship (Bonferroni corrected $\alpha = .025$) for participants with ASC ($r = .08, p = .774$), nor NT ($r = -.30, p = .262$). There was also no significant relationship between NT participants ratings on the AQ and the index of spatial modulation ($r = -.23, p = .427$).

**6.13. Experiment 9 Discussion**

Experiment 9 was designed to explore whether any issues with the spatial modulation of distractors were specific to visual-tactile judgements, or could be observed in a...
unisensory visual selective attention task. Both groups produced an interference effect to the distractor which was close to the visual target. The NT participants also produced an interference effect for the far distractor. The ASC participants produced a significantly reduced error rate in the congruent condition over baseline performance (a facilitation effect) when distractors were presented far from the hand. Critically, both groups showed a significant reduction in the interference effect between the near and far conditions. This suggests that participants with ASC were able to inhibit processing of distant distractors and the findings of Experiment 5 and 8 were not due to a general issue with selective attention. It is worth noting that congruent distractors did improve participants with ASC performance in the far condition, which could also reflect a failure of selective attention. However, participants were specifically instructed to focus on a stimulus (the green target) that was presented in the same sensory modality as the distractors. Interference effects were generally increased in Experiment 9 in comparison to Experiment 8 (see Figures 6.5 and 6.7). This is in line with the previous observation that unisensory interference effects are increased in comparison to those between vision and touch on a non-spatial task (Mast, Frings, & Spence, 2014). Importantly, the reduction in the interference effect between the near and far conditions in Experiment 9 indicates that participants in both groups were suppressing the processing of the spatially discrepant distractor.

6.14. Chapter 6 Discussion
The aims of the experiments reported in Chapter 6 were to further explore visual-tactile interactions in ASC following the findings of Experiment 5. The previously observed effect was replicated and a number of alternative accounts of these findings were ruled out. The present investigation suggests that the spatial modulation of visual-tactile interference effects may differ between individuals with ASC and NTs. This is unlikely to be the result of an extended representation of peripersonal space in ASC as a typical spatial redundancy effect was observed on a visual-tactile TOJ task. This suggests that the visual stimulus presented far from the hand was not perceptually bound with the tactile stimulus at shorter SOA. Performance was typical on this visual-tactile task which included no selective attention component. A recent study suggested that children with ASC show a reduced effect of visual reference frame on tactile judgements (Wada et al., 2014). Participants with ASC did not show the typical reduction in performance for bimodal tactile TOJs when their hands were crossed over the midline. NT children begin to show the crossed hands effect at around 6 years of age, and the effect is observed in late blind, but not congenitally blind children (Pagel, Heed, & Röder, 2009; Röder,
Rösler, & Spence, 2004). It may be that the representation of visual space becomes more closely mapped onto somatosensory representations later in development in ASC.

In Experiment 8 the reduced spatial modulation of visual distractors on a tactile judgement observed in participants with ASC in Experiment 5 was replicated. A number of studies in the NT literature have indicated that attending to a target in a particular sensory modality (such as touch) will typically direct attention in another modality (such as vision) to the same location as the target (see Driver & Spence, 1998; Driver & Spence, 1998). This leads to an increased interference of a distractor in a similar position, as observed here. Participants with ASC have displayed a similar interference effect when presented with a stimulus in the contralateral hemispace, suggesting that attention to touch is less effectively directed and extraneous stimuli are less effectively inhibited. This finding of reduced effectiveness of multisensory selective attention is in agreement with a previous study in adolescents with ASC (Murphy et al., 2014). An increased distractor effect was observed when participants selectively attended to a visual target in the presence of auditory distractors.

The current investigation suggests that this reduced selective attention does not generalise to a unisensory task. In Experiment 9 participants with ASC spatially modulated the same visual distractors as those used in Experiment 8 while making a visual judgement. Although interference effects were significantly decreased between the near and far condition for both groups, NT participant’s error rate was significantly increased over baseline performance in the far condition, an effect that was not observed in the ASC group. The reduced interference effect in the far location in participants with ASC in Experiment 9 supports the previous suggestion that visual attention may be more focussed in individuals with ASC than controls (Mann & Walker, 2003; Robertson et al., 2013; Ronconi et al., 2012). Moreover, the findings of Experiment 8 and 9 suggest multisensory selective attention is reduced in ASC, but this is not a general selective attention deficit.

The current investigation suggests at differential spatial selective attention within and between the sensory modalities in individuals with ASC. Participants with ASC show reduced spatial modulation of vision on a tactile judgement, while the modulation of vision on a visual judgement is typical. As has previously been described, selective attention in NTs is spatially allocated across the sensory modalities in a similar way to unisensory stimuli (Eimer, Van Velzen, & Driver, 2002; Holmes et al., 2006; Lloyd et al.,
Selective attention across the senses is closely linked in NTs. For instance, non-predictive tactile and auditory cues generate an ERP response at early stages of visual processing on a visual detection task (Kennett, Eimer, Spence, & Driver, 2001; McDonald & Ward, 2000). The current investigation suggests that cross and unimodal spatial attention are less closely linked in ASC in comparison to NTs. It is possible that differences in neural connectivity may contribute to these findings. Long range neural connectivity is thought to be reduced in ASC, with short range connections enhanced (Brock et al., 2002; Cherkassky et al., 2006; Itahashi et al., 2015). This may lead to less effective or delayed projection between unisensory brain regions. This could result in reduced modulation of irrelevant stimuli on crossmodal tasks, while processing within a modality may be intact.

It would be beneficial for future research to explore the inhibition of irrelevant information across other crossmodal judgements (for instance visual judgements in the presence of tactile distractors), and to explore differences in the neural signature of multisensory inhibition in individuals with ASC. Work of this nature will improve our understanding of how information from one modality may deleteriously affect performance in another modality in ASC, and help elucidate the mechanisms which underlie sensory overload (O’Neill & Jones, 1997). It is also worth mentioning that the performance of participants with ASC on many tasks of this nature might also be understood within the perceptual load framework (Lavie, 1995), which is emerging as an explanation for differences in selective attention in ASC. This gives that the increased effect of distractors on performance could be a result of participants with ASC having an enhanced perceptual capacity (Remington, Swettenham, & Lavie, 2012). In conditions of increased perceptual load, participants with ASC have more available attentional resources and show an increased effect of distractors, which has been observed within (Remington et al., 2012; Remington, Swettenham, Campbell, & Coleman, 2009), and between the senses (Tillmann, Olguin, Tuomainen, & Swettenham, 2015). It was not possible to test this using the current paradigm as perceptual load was not manipulated. Perceptual load is independent of task difficulty and refers to conditions whereby there is a large amount of distracting information (Lavie, 2005). This remains an interesting avenue for future research.

In the present investigation we explored the spatial modulation of visual-tactile interactions in adults with ASC. We have shown that participants with ASC exhibit reduced spatial modulation of an irrelevant visual distractor on a tactile judgement. This
may be attributed to a specific issue involving selective attention to touch in the presence of visual information.
Chapter 7

General discussion
7.1. Summary
The work presented in this thesis has explored multisensory processing in adults with ASC, with a particular focus on the interaction between vision and touch. A summary of the aims, findings and an explanation for each experiment are included in Table 7.1. This final chapter will revisit the multisensory processes that have been investigated. General themes emerging from this work and future directions are also discussed.

7.2. Cue-combination
Experiment 1 revealed no significant differences in performance between participants with ASC and NTs on a visual-haptic size judgement task. Multisensory performance of both groups differed from the predictions of a statistically optimal Maximum Likelihood Estimation (MLE) model, but approximated a cue-switching (SCS) model. We therefore failed to replicate the optimal combination of multisensory cues in our adult NT group which has previously been a robust predictor of performance on tasks of this nature (e.g. Ernst & Banks, 2002; Gori, Del Viva, Sandini, & Burr, 2008). This may be attributed to the methodological issues which are detailed in section 2.6.4. Participants may have been encouraged to adopt a cue-switching strategy as the spatial offset between the cues, combined with the dual modality stimuli only being presented in a condition of conflict, may have caused participants to avoid combining the cues. However, there was considerable variability in performance across both groups (represented in Figure 2.15). The dual modality performance of a small number of participants fell close to the MLE model predictions. It is possible that these individuals were more tolerant of spatial discrepancies between stimuli which may have encouraged the interaction between the visual and haptic cues, despite the spatial discrepancy.

Although optimal cue-combination in NT participants was not replicated on this task, the typical performance (given by similarity to NT performance) of participants with ASC is nevertheless a novel finding. This is the first study to investigate visual and haptic size judgements in participants with ASC and indicates that performance is comparable to controls using a paradigm where the cues are not combined. There is emerging evidence that individuals with ASC combine within and between modality cues in an optimal manner. Recent studies have indicated that the combination of visual texture and disparity cues when making judgements about slant (Bedford, Pellicano, Mareschal, & Nardini, 2015), and visual and vestibular cues when making judgements about self-motion (Zaidel et al., 2015) are approximated by MLE predictions in participants with ASC.
**Table 7.1. Summary of findings of each experiment**

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<th>Findings</th>
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<td><strong>Experiment 1</strong>: Visual haptic cuecombination (ASC)</td>
<td>Visual-haptic size judgements compared with the predictions of a statistically optimal MLE model</td>
<td>Performance of participants with ASC and NT was not well predicted by the MLE model, but was comparable to a non-optimal SCS model</td>
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<tr>
<td><strong>Experiment 2 and 3</strong>: Temporal and spatial CCT (ASC)</td>
<td>Develop a version of the CCT for measuring visual-tactile interactions over time and space in ASC.</td>
<td>NT Participants produced visual-tactile interactions to stimuli which occurred close together in time and space. Tactile temporal acuity thresholds well correlated with autistic traits.</td>
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<td><strong>Experiment 4 and 5</strong>: Temporal and spatial CCT (ASC)</td>
<td>Exploring visual-tactile interactions over time and space in ASC.</td>
<td>Both groups produced visual-tactile interactions to near simultaneous stimuli. Participant’s with ASC produce visual-tactile interactions to a distractor present far from the stimulated hand which was not observed in NTs</td>
</tr>
<tr>
<td><strong>Experiment 6</strong>: Uni and multisensory temporal sensitivity (ASC)</td>
<td>Exploring uni and multisensory temporal sensitivity across a range of sensory modalities in ASC.</td>
<td>No significant differences in uni or multisensory sensitivity between the groups. PSEs for audio-visual pairings correlated with sensory traits in participants with ASC.</td>
</tr>
<tr>
<td><strong>Experiment 7</strong>: Visual-tactile TOJs (ASC)</td>
<td>Investigating the representation of peripersonal space in ASC.</td>
<td>Both groups showed a similar benefit of spatial redundancy on TOJs</td>
</tr>
<tr>
<td><strong>Experiment 8</strong>: Spatial CCT (ASC)</td>
<td>Replicating Experiment 5 using fewer distractor locations.</td>
<td>Effects of Experiment 5 replicated: participants with ASC produced visual-tactile interactions to a spatially discrepant distractor.</td>
</tr>
<tr>
<td><strong>Experiment 9</strong>: VCT in participants with ASC</td>
<td>Investigating visual spatial modulation of interference in ASC.</td>
<td>Participants with ASC appropriately modulated effect of far distractor on visual judgement.</td>
</tr>
</tbody>
</table>
There would be a benefit in replicating Experiment 1 using virtual reality equipment (similar to Ernst & Banks, 2002) to further characterise the combination of multisensory cues, with consideration of the issues highlighted in this study. Using virtual reality equipment would allow visual-haptic cues to be presented in conflict with no perceptible spatial discrepancy. This may encourage participants to combine the cues rather than switch between them as in Experiment 1. Furthermore, using computer generated stimuli would enable the use of adaptive methods to determine response parameters rather than the method of constant stimuli. This would allow a specific level of performance to be determined in each condition at greater speed. This is difficult to achieve using real life apparatus as the number of available levels are limited to the stimuli that have been made.

**7.3. Temporal processing**

*Unisensory*

In Experiment 4, a significant correlation between tactile temporal acuity and NT individual’s AQ scores was observed, such that individuals with more autistic traits produced increased tactile thresholds. As autistic traits were associated with tactile temporal acuity, we expected that between-group differences in thresholds would be observed and highlighted the usefulness of presenting participants with stimuli at threshold level on the CCT. However, there were no significant differences across the experiments in which tactile thresholds were measured, although in Experiment 6 there was considerable variability in tactile thresholds in the ASC group using a different type of tactile stimulation (generated by sine waves rather than white noise) presented for a shorter duration (8ms rather than 80ms).

The link between autistic traits and clinical ASC is not currently well defined. ASC is believed to lie at the extreme of a distribution of autistic traits across the general population (Baron-Cohen et al., 2001). Autistic traits predict atypical sensory functioning (Robertson & Simmons, 2013), and there is evidence that individuals reporting high autistic traits share some neural changes with clinical autism, such as reduced neural connectivity (Jakab et al., 2013; von dem Hagen et al., 2011). However, sensory processing, and the neural differences which likely underlie them, are poorly understood in clinical ASC. Although the Autism Spectrum Quotient (AQ) represents a useful tool for characterising NT groups, more research is required to improve our understanding of the relationship between autistic traits and the clinical condition. Despite this consideration, the relationship between autistic traits and tactile processing
highlighted individual differences in unisensory processing in NTs which have not previously been considered in many multisensory studies. The adapted CCT developed in this thesis was a useful approach to investigating the temporal and spatial limits of visual-tactile interactions while constraining individual unisensory performance. This was successfully developed into a visual task in Experiment 9. In addition to the interesting findings reported here, reduced spatial modulation of visual-tactile interactions in older participants has also been observed using this paradigm (Couth, Gowen, & Poliakoff, 2015). This method represents a useful approach to exploring visual- tactile processing both in the typical population and other heterogeneous populations.

In Experiment 6 there were no statistically significant differences in unisensory thresholds between participants with ASC and NT. However, there was considerable variability in ASC participant thresholds, particularly in the visual and tactile conditions. Although this represents a useful contribution to the literature on temporal processing within the modalities in ASC, it is worth mentioning that the design of the experiment may have contributed to some of the variability in the data. A single staircase procedure was used to determine participant thresholds in each condition. However, accuracy can be improved, for example, by using multiple staircase procedures per condition and taking the threshold as the average reached on each procedure. It is possible that using only one staircase procedure in each condition may have produced less accurate thresholds and thus contributed to some of the variability in ASC participant thresholds. Unisensory temporal processing remains an interesting area for further research in ASC.

**Multisensory processing**
The experiments reported in this thesis have revealed that multisensory temporal processing is not significantly different from controls (Experiments 4 and 6). This contradicts a number of previous studies which have revealed reduced temporal modulation of audio-visual interactions and sensitivity to audio-visual stimuli in children with ASC (e.g. Foss-Feig et al., 2010; Stevenson, Siemann, Schneider, et al., 2014), but is in agreement with a recent study which found temporal processing was comparable to controls in a group of adolescents and young adults (de Boer-Schellekens, Keetels, et al., 2013). This suggests that the maturation of multisensory temporal sensitivity is delayed in ASC. However, it is worth noting that a number of the previous studies which have explored temporal processing in ASC have used paradigms which may be influenced by the participant’s response criterion. It is possible that criterion setting may differ from NTs and contribute to previously observed group differences. For example, Foss-Feig et
al. (2010) asked participants if they had seen a double or single flash when presented with a double beep (flash beep illusion). The children with ASC produced illusory responses significantly more frequently than baseline across consecutive SOA up to ± 300ms (see Figure 4.1) with the authors concluding that audio-visual temporal modulation is reduced in ASC. However, the children with ASC reported the illusory flash on 25% of trials even at the most extreme SOA (500ms). It is possible that this reflects a difference in response criterion rather than a genuine perceptual issue, i.e. the children with ASC were more inclined to produce double flash responses whenever double beeps were heard. Future research could explore the developmental trajectory of multisensory temporal sensitivity in ASC across adolescence and into adulthood. Utilising methods which are less influenced by response strategy such as 2AFC procedures, or which enable the decision making and sensory components to be isolated (e.g. Lesmes et al., 2015), will help disentangle the mechanisms which underlie these apparent differences in multisensory processing.

Experiment 6 revealed considerable variability in multisensory sensitivity in participants with ASC. This may reflect individual differences in compensatory strategies, the development of multisensory processing or (as mentioned above) response strategy. It is possible that factors which were not controlled or measured in the current experiment may also have contributed to some of this variability in performance. For instance, the use of action video games is associated with improved audio-visual temporal acuity (Donohue, Woldorff, & Mitroff, 2012). As video-game use is high among individuals with ASC (Mazurek & Wenstrup, 2012), it would be worth including some measure as a factor to control in future studies investigating multisensory temporal processing.

Sampling issues may also reflect some of the variability in the studies presented in this thesis. To ensure experiments were sufficiently powered a liberal selection criteria was used. Accordingly, symptom rating (as measured using the ADOS), IQ and age were somewhat variable in our ASC groups. It is possible that these factors may have contributed to the variability in our data. Despite this consideration, an ASC group is likely to be diverse even when recruiting a sample which is similar in age, IQ and symptom rating. ASC is a highly heterogeneous condition and it has previously been noted that producing reliable between-group differences across studies presents a major challenge in autism research (Simmons et al., 2009). The presentation of behaviours which define ASC vary between individuals and may overlap across a
number of neurodevelopmental conditions with distinct aetiologies (Coleman & Gillberg, 2012). Moreover, it has been suggested that the triad which is used to diagnose ASC may represent discreet conditions (see Happé & Ronald, 2008). A number of population and gene studies have suggested that social and communication issues, and restricted or repetitive patterns of behaviour are heritable, but unlikely to develop from a single cause. This is likely to add considerable variability to performance within and between studies, a situation which is exacerbated as sample sizes in ASC studies tend to be small. Attempting to identify sub-groups within an ASC sample that produce atypical performance (Charman et al., 2011), or investigating factors that drive variability rather than making comparisons between average performance between ASC and NT participants are approaches to dealing with this challenge. For instance, in Experiment 6 we revealed a relationship between PSE in the audio-visual condition and self-reported sensory traits. This interesting finding suggests that attention to vision may contribute to sensory symptoms in ASC. It would be interesting to follow this finding up to explore whether this bias underlies compensatory strategies used by certain individuals with ASC. This finding is discussed further below.

7.4. Spatial processing
The work presented in this thesis has produced a number of novel insights into spatial processing of multisensory stimuli in ASC. In Experiment 5, participants with ASC produced an increased error rate in response to visual distractors presented in the opposite hemispace to a tactile target. This effect was not observed in NT controls and suggested that spatial modulation of visuotactile interactions may be reduced in ASC. In Experiment 7, we used a visual-tactile TOJ task to further explore spatial processing in ASC. For both groups, temporal acuity was improved when visual stimuli were presented in a location distant from the stimulated hand. This task was used to explore the possibility that the findings of Experiment 5 were due to an extended representation of peripersonal space in ASC. However, it has also been suggested that spatial redundancy effects may be the result of the processing of disparate stimuli using less cognitive resources (Zampini et al., 2003a). By this account, stimuli which are presented in the same hemispace are initially received by the same brain hemisphere, overloading resources and reducing TOJ performance. When the stimuli are presented in ipsilateral locations, this overloading is reduced and performance is improved. The fact that participants with ASC showed this benefit indicates that they are able to separately process spatially discrepant stimuli. Nevertheless, the representation of
peripersonal space in ASC should be investigated further. Future research could examine any super-additive neural response to visual-tactile stimuli presented coincidently, or from separate locations (e.g. Sambo & Forster, 2008) as a direct measure of visual-tactile integration in near and far space in ASC. Alternatively, multisensory body illusions across spatial discrepancies (e.g. Botvinick & Cohen, 1998; Lloyd, 2007) could be utilised to improve our understanding of the representation of peripersonal space in ASC.

Interestingly, attention across different sensory modalities emerged as a particularly salient theme of the work presented here rather than the combination of information across modalities. Spatial modulation of visual distractors on a tactile judgement was investigated in Experiments 5 and 8 and was reduced in participants with ASC. This effect cannot be explained by a general deficit in selective attention, as participants with ASC showed spatial modulation during a visual judgement with a visual distractor in Experiment 9. These differences were observed within the participant groups rather than through significant between group differences. In Experiment 5, we highlighted reduced spatial modulation of visual-tactile interactions within the ASC data and sought to focus on this effect in later experiments. As autism is a highly heterogeneous condition, it is likely that individual differences would wash out any statistically significant between group differences with the sample sizes that were available here. Accordingly, we highlight this preliminary effect of reduced spatial modulation in ASC as an interesting finding which warrants further investigation.

These findings suggest there is a specific deficit in visual-tactile selective attention in ASC, such that irrelevant visual information produces a greater effect on tactile judgements. Specifically, the findings of these experiments suggest that during selective attention to a tactile target, the spatial modulation of visual distractor processing is reduced in ASC. As has previously been established in traditional versions of the CCT (see Pavani, Spence, & Driver, 2000; Spence, Pavani, & Driver, 1998; Spence, Pavani, & Driver, 2004) visual-tactile interactions were spatially modulated in NT participants in Experiments 3, 5 and 8. Selectively attending to stimuli in a particular modality will direct attention in another modality to the same location, while irrelevant information presented further away will be inhibited (Spence & Driver, 2004; Spence, 2002). This allows more efficient processing of a stimulus; information which appears in the same location can be preferentially processed by multiple modalities automatically. This provides a richer percept of the stimulus as more information can be conveyed by
multiple sensory modalities. To prevent an overwhelming perceptual experience, stimuli presented further away must be suppressed. However, participants with ASC showed similar effects for both the distractor presented close to and far from the hand in Experiments 5 and 8, suggesting that the selection of the target and/or the inhibition of distant interfering visual information were reduced.

There are a number of avenues of interest that might be explored in future research to improve understanding of atypical visual-tactile processing in ASC, specifically the contribution of response conflict and enhanced processing capacity to the reduced spatial modulation of visual distractors on tactile judgements observed here. The influence of visual distractors on the CCT has been attributed to both basic perceptual processing and higher level response competition (Spence, Pavani, Maravita, et al., 2004). The response competition account proposes that incongruent stimuli co-occurring with the target can cause conflict during information processing, leading to an influence on the participant’s response. Both basic perceptual effects and response conflict would likely contribute to an overwhelming experience of the environment in ASC. An EEG study in NT participants revealed an enhanced N2 component prior to the participant’s response when presented with incongruent visual distractors, consistent with a significant role of response conflict on performance on the CCT (Forster & Pavone, 2008). Repeating the adapted CCT while measuring ERPs could elucidate the contributions of basic perceptual and information processing to the effect reported here. To investigate the role that an enhanced perceptual capacity may contribute to increased distractor processing in ASC, related experiments could be designed in which visual perceptual load is manipulated while participants make tactile judgements. If processing capacity is increased in comparison to NTs, increased distractor effects at high levels of perceptual load would be anticipated in participants with ASC as has previously been observed in visual (Remington et al., 2012; Remington et al., 2009) and visual-auditory tasks (Tillmann et al., 2015). Focusing on the mechanisms which contribute to the reduced spatial modulation of visual-tactile processing observed here could ultimately lead to the development of effective targeted interventions.

It may be that atypical neural functioning in ASC leads to visual information appearing particularly salient when presented concurrently with another sensory modality, making irrelevant visual stimuli difficult to suppress. This may relate to the experience of sensory overload which is often reported by individuals with ASC (O’Neill & Jones, 1997). This is consistent with the observation that PSEs for audio-visual judgements were well correlated with sensory traits in participants with ASC (Experiment 6). Visual
information in the pairings may be perceived as more salient, leading to the visual stimuli being processed more quickly (Smith, 1933; Spence & Parise, 2010), and perceived first across a greater range of SOAs. In turn this would lead to a bias in the PSEs towards the auditory modality in this experiment. Participants who produced this effect also reported more everyday sensory issues. It would therefore be of interest to explore whether this reduced spatial modulation is observed for audio-visual judgements and related to sensory traits in ASC.

7.5. Conclusions
The aim of this thesis was to further characterise multisensory processing in ASC. Perception of the world involves a number of mechanisms related to the combination of information from multiple sensory sources. Exploring multisensory processing is important as it may be relevant to the aetiology of sensory abnormalities experienced by many people with ASC. We began this project with a focus on multisensory interactions in ASC. The work presented here provides no evidence that visual-haptic cue processing and temporal processing of multisensory information in adults with ASC differs from NTs. However, individual differences in multisensory processing in both NT and individuals with ASC should to be considered in future work. Rather than differences being found in multisensory combination, the work in this thesis has implicated atypical multisensory selective attention in ASC. For participants with ASC, an increased visual bias on an auditory-visual task was related to greater reports of everyday sensory atypicalities. Moreover, selective attention to tactile stimuli while presented with extraneous visual information appears to be reduced in participants with ASC. These novel findings may provide an explanation for the experiences of sensory overload experienced by many people with ASC. We hope that this work will motivate other researchers to explore these effects and ultimately lead to the development of effective sensory interventions which might provide a benefit to people with ASC.
References


Appendix A

A1 The Psychometric function

The psychometric function is a widely used psychophysical technique to model the relationship between a stimulus which varies according to some property and the participant’s response to that stimulus. In the example of Figure A taken from Chapter 2, the participant is presented with blocks ranging in height which are compared to a standard which is fixed in height. The proportion of times the participant judges each block to be taller than the standard is plotted, giving each data point.

A psychometric function can then be fitted to these data points. In the experiments reported in Chapters 2, 5 and 6 data was fit to cumulative Gaussian functions using the Palamedes toolbox for MATLAB (Kingdom & Prins, 2009). Two parameters are left free to vary in the fitting process, $\mu$ and $\beta$. These parameters are of interest as they are believed to relate to the sensory mechanism under investigation. In the experiments reported in this thesis $\mu$ gives the mean of the fitted curve (the 0.5 point) referred to as the point of subjective equality (PSE). The PSE approximates the point at which the participant considers the stimulus to be equal in 2IFC procedures. The PSE is a measure of the participant’s bias in the sensory estimate. $\beta$ gives the slope, which is an important measure of sensitivity. A steeper slope relates to a narrower Gaussian distribution and reduced variability in the participant’s responses. Experiment 1 use the SD ($\sigma$) as a measure of sensitivity which is calculated as $\frac{1}{\beta}$. In Experiment 6 and 7, the just noticeable difference (JND) is calculated which is calculated as $\frac{0.675}{\beta}$. The ± 0.675 point is equivalent to the 75% and 25% points on a cumulative Gaussian distribution and the JND is believed to represent the smallest quantity by which a stimuli can be increased for the participant to detect a chance 75% of the time (Zampini et al., 2003a, 2003b; Zampini, Brown, et al., 2005). The JND is reported as a measure of sensitivity in these experiments in keeping with convention of previous temporal order judgement studies.

Two further parameters are important in the fitting process. $\gamma$ refers to the participant’s estimated guessing rate and $\lambda$ the frequency of trials answered incorrectly due to lapses in attention (e.g. sneezing during a trial). These parameters are not of experimental interest here and are fixed. In line with the recommendations of Kingdom and Prins (2009) values close to 0 were chosen.
Figure A1 A sample Psychometric function from Experiment 1 including parameters of experimental interest in this thesis. The mean of the fitted curve $\mu$ gives the PSE which is used as a measure of bias. The slope ($\beta$) is a measure of sensitivity and is used to calculate the SD (Experiment 1) and JND (Experiments 6 and 7).
Appendix B

B1 Experiment 1 pilot study
The aim of this experiment was to pilot test an adapted version of the visual-haptic size discrimination task (Ernst & Banks, 2002; Gori et al., 2008). It was anticipated that NT participant’s SD and PSE data would approximate the predictions of the MLE model.

Participants
Twelve participants (four female; two left handed) with a mean age of 26.42 years (± 2.64) were recruited from the student population and staff of the University of Manchester and were compensated with £10 payment.

Apparatus, Design and Procedure
The apparatus design and procedure were similar to that reported in Experiment 1. Participants made comparative height judgements in a 2AFC procedure using the method of constant stimuli. Participants made these judgements in unisensory visual and haptic conditions, and a dual modality condition. The dual modality condition included standards conflict 1 and 2. A no conflict standard was also included in which the blocks either side of the cartridge were the same height (55mm). The comparison stimuli 53 and 57mm in height which were used in Experiment 1 were not included here.

Analysis

SD data
An MLE prediction of performance was calculated according to equation 1. This prediction was compared with performance in the dual modality condition, visual and haptic conditions using a within participant ANOVA. Significant interactions were followed up using paired sample t-tests.

PSE data
An MLE prediction of PSE in each dual modality condition was calculated according to equation 4. The variance predicted by the MLE model and a model of complete visual and haptic capture were compared using equation 7.

Results

SD data
The mean SD in each condition is plotted in Fig B.1 A within participants ANOVA was conducted to compare performance in each condition. A multisensory enhancement in performance would be indicated by a reduced SD in the dual modality condition in comparison to either unisensory condition. Furthermore, if participants were combining
the visual and haptic stimuli in a statistically optimal manner then the SD measured in
the no-conflict condition should be statistically indistinguishable from the SD predicted
by the MLE model.

A within participants ANOVA (Greenhouse-Geisser adjustment) revealed that the size of
the SD differed significantly between the conditions (F (3, 33) = 9.64, p < .001, \( \eta^2 = .467 \)).
As would be expected, paired sample t-tests (Bonferronni corrected, \( \alpha = .008 \)) revealed
the visual SD (t (11) = 5.50, p < .001, \( d = 2.65 \)) and haptic SD (t (11) = 5.58, p < .001, \( d =
1.61 \)) were significantly larger than the SD predicted by the MLE model. Critically, the SD
predicted by the dual modality condition was significantly larger than that predicted by
the MLE model (t (11) = 4.13, p = .002, \( d = 2.00 \)). The dual modality SD was statistically
indistinguishable from the haptic SD (t (11) = 2.15, p = .055, \( d = 1.07 \)) and the visual SD (t
(11) = 1.49, p = .165, \( d = 0.33 \)). The visual and haptic SD were also statistically
indistinguishable (t (11) = 1.66, p = .124, \( d = 0.88 \)).

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Figure B1 Mean SD measured in each unisensory condition, the non-conflict multisensory
condition and that predicted by the MLE model derived from the unisensory estimates
according to equation 5. Error bars represent within participant CI (Cousineau, 2005).

**PSE data**
Measured and predicted PSE data for each participant are included in Figure B.2.

The proportion of variance of the PSE data that was explained by visual capture, haptic
capture and the MLE model were compared using equation 6. For visual capture, \( R^2 = -
3.01 \), for haptic capture, \( R^2 = -3.81 \) and for the MLE model \( R^2 = -0.50 \).
Figure B2 Each participant’s PSEs plotted as a function of cue-conflict in each of the dual modality conditions; standard (asterix), conflict 1 (cross), and conflict 2 (circle). The dotted black line is the best linear fit of the measured data points for each participant. The solid black line is the MLE prediction for that participant, the red line is the prediction for complete visual dominance and the blue line for complete haptic dominance.

Discussion

The optimal combination of visual-haptic cues was investigated in this experiment. An MLE prediction of statistically optimal multisensory SD was calculated from the unisensory estimates. This MLE prediction was significantly lower than the SD measured in the dual modality condition. The dual modality SD was comparable to both the unisensory visual and haptic conditions. Analysis of the PSE data revealed that the MLE model provided a better prediction of the measured PSE values than visual capture or haptic capture, but that this was no better than the group mean.

Participant’s performance was not well predicted by the MLE model. The statistically optimal weighting of visual and haptic cues for size judgements were not captured in the present experiment (Ernst & Banks, 2002; Gori et al., 2008). Moreover, participants did not produce a performance enhancement in the dual modality condition, which is an index of multisensory processing and critical to the MLE model (see equation 5).

Explanations for this are considered below and informed the design of Experiment 1.

The procedure of Gori et al (2008) was closely replicated, with a number of adaptations to increase experimental control and reduce testing time. Firstly, the inter stimulus interval was constrained to ensure the effects of working memory decay remained
approximately constant in all conditions. In the Gori et al study the interstimulus interval was not reported and may have varied between conditions and participants. Second, the presentation of visual stimuli were controlled with occluding spectacles while participants in the Gori et al study opened and closed their eyes when instructed by the experimenter. Third, in the Gori et al study comparison block sizes increased in 1mm increments, while the current study used increments of 2mm.

Performance measured in the unisensory visual condition may have been close to ceiling in the present experiment, leaving no room for a multisensory enhancement. In the Gori study adult participants produced an average SD of 4mm in the visual condition, almost double that here. The PLATO occlusion spectacles do not become opaque when closed, but remain translucent. Adaptation to new light levels when the spectacles go from closed to open when the stimulus is presented is likely to be reduced in comparison to opening one’s eyes (see Milgram, 1987). Thus, the participant may have had a clear visual image for more of the 1000ms stimulus presentation than in the Gori et al study, leading to improved performance in the unisensory condition. The comparison stimuli used here may have lacked the sensitivity to capture a subtle improvement in dual modality performance over the unisensory visual condition.

Additional comparison blocks were included in each condition in Experiment 1 to improve the sensitivity of the Psychometric function so differences between the conditions could be investigated more clearly when exploring visual-haptic cue combination in participants with ASC.
B2 Within group differences in cue-combination in Experiment 1

Distance from MLE prediction

A root square difference (RSD) score was calculated for each participant. This was given as

$$\sqrt{\sum (PSE_{predicted_i} - PSE_{measured_i})^2}$$

Where i refers to each conflict condition.

This RSD score was used as an index of how each participant’s PSE measured in the cue-conflict conditions differed from the prediction of the PSE from the MLE model. An RSD score is included with each participant’s psychometric function in Appendix D. The groups were then split at the median to divide the group into those whose PSEs were close to the predictions from the MLE model (low RSD value) and those that were further from the MLE model (higher RSD score).

Mixed ANOVAs with group (ASC, NT) as the between participants variable was then used to explore differences in the SD between the conditions for participants producing high and low RSD values. Significant effects and interactions were followed up with within and between group t-tests.

Low RSD participants.

A mixed ANOVA (Greenhouse-Geisser adjustment) with group as the between participants factor revealed a significant effect of condition ($F (2.07, 22.74) = 15.22, p < .001, \eta_p^2 = .581$). This effect was followed up with paired sample t-tests (Bonferroni corrected, $\alpha = .008$). Critically, the MLE prediction of SD was significantly lower than the dual modality SD ($t (12) = 4.77, p < .001, d = 1.74$). The visual SD was lower than the dual modality SD, but this difference was not statistically significant ($t (12) = 2.79, p = .017, d = 0.95$). The dual modality SD was smaller than the haptic SD, but this difference was not statistically significant ($t (12) = 1.35, p = .204, d = 0.43$). The MLE prediction was lower than the visual SD ($t (12) = 3.76, p = .003, d = 0.82$) and haptic SD ($t (12) = 7.46, p < .001, d = 2.43$). The visual SD was significantly lower than the haptic SD ($t (12) = 3.87, p = .002, d = 1.51$).

There was no significant group x condition interaction ($F (2.07, 22.74) = .23, p = .802, \eta_p^2 = .021$)
High RSD participants
A mixed ANOVA (Greenhouse-Geisser adjustment) with group as the between participants factor revealed a significant effect of condition ($F(1.98, 21.73) = 9.05, \, p = .001, \, \eta^2_p = .451$). This effect was followed up with paired sample t-tests (Bonferonni corrected, $\alpha = .008$). Critically, the MLE model prediction was significantly lower than the dual modality condition ($t(12) = 4.11, \, p = .001, \, d = 1.79$). The visual condition was significantly lower than the dual, but this was not statistically significant ($t(12) = 1.90, \, p = .081, \, d = 0.81$), the dual condition was significantly lower than the haptic condition ($t(12) = 1.51, \, p = .157, \, d = 0.61$). The MLE prediction of SD was lower than the visual SD although this difference was not statistically significant ($t(12) = 3.08, \, p = .010, \, d = 0.57$), and significantly lower than the haptic SD ($t(12) = 4.92, \, p < .011, \, d = 1.89$). The visual condition was significantly lower than the haptic condition ($t(12) = 3, \, p = .011, \, d = 1.15$).

There was no significant group x condition interaction ($F(1.98, 21.73) = .01, \, p = .999, \, \eta^2_p = .001$).
B3 Experiment 1 Psychometric functions

ASC 1
Visual SD = 2.27
Visual PSE = -0.19
Haptic SD = 2.02
Haptic PSE = -0.33
Conflict 1 SD = 1.78
Conflict 1 PSE = 0.31
Conflict 2 SD = 1.395
Conflict 2 PSE = -1.26
RSD score = 1.744

ASC 2
Visual SD = 3.14
Visual PSE = -0.05
Haptic SD = 3.10
Haptic PSE = -0.96
Conflict 1 SD = 3.03
Conflict 1 PSE = 1.66
Conflict 2 SD = 5.31
Conflict 2 PSE = -3.43
RSD score = 3.86

ASC 3
Visual SD = 1.24
Visual PSE = 0.57
Haptic SD = 3.48
Haptic PSE = -0.24
Conflict 1 SD = 1.57
Conflict 1 PSE = 1.88
Conflict 2 SD = 1.99
Conflict 2 PSE = 2.11
RSD score = 0.47

ASC 4
Visual SD = 2.62
Visual PSE = 0.44
Haptic SD = 4.19
Haptic PSE = 0.78
Conflict 1 SD = 3.57
Conflict 1 PSE = -0.18
Conflict 2 SD = 2.78
Conflict 2 PSE = 1.56
RSD score = 4.20
ASC 5
Visual SD = 1.29
Visual PSE = 0.32
Haptic SD = 3.88
Haptic PSE = -0.73
Conflict1 SD = 3.46
Conflict1 PSE = 1.14
Conflict2 SD = 3.82
Conflict2 PSE = -0.53
RSD score = 2.25

ASC 6
Visual SD = 1.78
Visual PSE = -0.07
Haptic SD = 2.45
Haptic PSE = -0.13
Conflict1 SD = 1.68
Conflict1 PSE = 0.81
Conflict2 SD = 2.12
Conflict2 PSE = -0.08
RSD score = 2.25

ASC 7
Visual SD = 1.43
Visual PSE = 0.78
Haptic SD = 2.31
Haptic PSE = 0.43
Conflict1 SD = 2.74
Conflict1 PSE = 1.05
Conflict2 SD = 3.73
Conflict2 PSE = -0.84
RSD score = 0.58

ASC 8
Visual SD = 2.63
Visual PSE = 0.44
Haptic SD = 4.19
Haptic PSE = 0.78
Conflict1 SD = 3.58
Conflict1 PSE = -0.18
Conflict2 SD = 1.56
Conflict2 PSE = 2.78
RSD score = 4.35
ASC 9
Visual SD = 2.12
Visual PSE = -0.62
Haptic SD = 3.30
Haptic PSE = -0.96
Conflict1 SD = 3.34
Conflict1 PSE = -0.21
Conflict2 SD = 2.98
Conflict2 PSE = 2.98
RSD score = 1.82

ASC 10
Visual SD = 1.87
Visual PSE = 0.24
Haptic SD = 8.06
Haptic PSE = -0.61
Conflict1 SD = 3.16
Conflict1 PSE = 1.24
Conflict2 SD = 3.71
Conflict2 PSE = -0.47
RSD score = 2.66

ASC 11
Visual SD = 2.06
Visual PSE = -0.31
Haptic SD = 3.36
Haptic PSE = 0.82
Conflict1 SD = 3.27
Conflict1 PSE = 1.31
Conflict2 SD = 3.32
Conflict2 PSE = -0.34
RSD score = 1.03

ASC 12
Visual SD = 1.85
Visual PSE = 0.10
Haptic SD = 1.68
Haptic PSE = 0.74
Conflict1 SD = 4.06
Conflict1 PSE = 3.82
Conflict2 SD = 3.24
Conflict2 PSE = -2.07
RSD score = 4.75
ASC 13
Visual SD = 2.01
Visual PSE < .01
Haptic SD = 2.65
Haptic PSE = -0.26
Conflict1 SD = 3.43
Conflict1 PSE = 2.49
Conflict2 SD = 1.37
Conflict2 PSE = -2.26
RSD score = 3.78

NT1
Visual SD = 2.77
Visual PSE = 0.41
Haptic SD = 4.49
Haptic PSE = -0.39
Conflict1 SD = 4.93
Conflict1 PSE = 1.72
Conflict2 SD = 4.14
Conflict2 PSE = 0.42
RSD score = 1.81

NT 2
Visual SD = 1.52
Visual PSE = -0.46
Haptic SD = 2.74
Haptic PSE = -0.26
Conflict1 SD = 4.76
Conflict1 PSE = -0.76
Conflict2 SD = 2.84
Conflict2 PSE = 2.27

Figure B3: Psychometric functions for each participant with ASC. The left box displays unisensory visual (red plus sign) and haptic (blue squares) conditions. The right displays conflict 1 (green upward triangles) and conflict 2 (magenta downward triangle) conditions. RSD scores are included for each participant (see Appendix B2) this score was calculated as the difference between participants PSE in each conflict condition and the MLE prediction.
NT 3
Visual SD = 2.42
Visual PSE = 0.36
Haptic SD = 4.54
Haptic PSE = 0.76
Conflict1 SD = 1.57
Conflict1 PSE = -1.14
Conflict2 SD = 4.07
Conflict2 PSE = 0.11
RSD score = 3.36

NT 4
Visual SD = 2.38
Visual PSE < -.01
Haptic SD = 3.99
Haptic PSE = 0.26
Conflict1 SD = 2.18
Conflict1 PSE = 2.49
Conflict2 SD = 1.63
Conflict2 PSE = -1.64
RSD score = 1.09

NT 5
Visual SD = 1.65
Visual PSE = 0.12
Haptic SD = 4.42
Haptic PSE = -0.39
Conflict1 SD = 5.53
Conflict1 PSE = -1.99
Conflict2 SD = 5.51
Conflict PSE = 3.60
RSD score = 7.25

NT 6
Visual SD = 1.45
Visual PSE = -0.02
Haptic SD = 2.57
Haptic PSE = -0.201
Conflict1 SD = 1.59
Conflict1 PSE = 0.41
Conflict2 SD = 1.51
Conflict2 PSE = -0.69
RSD score = 1.42
<table>
<thead>
<tr>
<th>NT 7</th>
<th>Visual SD = 5.99</th>
<th>Visual PSE = -0.32</th>
<th>Haptic SD = 4.71</th>
<th>Haptic PSE = -0.04</th>
<th>Conflict1 SD = 2.77</th>
<th>Conflict1 PSE = -2.73</th>
<th>Conflict2 SD = 3.44</th>
<th>Conflict2 PSE = 3.43</th>
<th>RSD score = 2.46</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT 8</td>
<td>Visual SD = 2.27</td>
<td>Visual PSE = 0.71</td>
<td>Haptic SD = 4.37</td>
<td>Haptic PSE = 0.10</td>
<td>Conflict1 SD = 3.19</td>
<td>Conflict1 PSE = 3.57</td>
<td>Conflict2 SD = 2.02</td>
<td>Conflict2 PSE = -2.67</td>
<td>RSD score = 1.75</td>
</tr>
<tr>
<td>NT 9</td>
<td>Visual SD = 3.28</td>
<td>Visual PSE = -0.35</td>
<td>Haptic SD = 2.06</td>
<td>Haptic PSE = -0.46</td>
<td>Conflict1 SD = 3.12</td>
<td>Conflict1 PSE = 0.91</td>
<td>Conflict2 SD = 3.35</td>
<td>Conflict2 PSE = -0.03</td>
<td>RSD score = 2.58</td>
</tr>
<tr>
<td>NT 10</td>
<td>Visual SD = 3.29</td>
<td>Visual PSE = -0.35</td>
<td>Haptic SD = 2.07</td>
<td>Haptic PSE = 0.46</td>
<td>Conflict1 SD = 3.12</td>
<td>Conflict1 PSE = 0.91</td>
<td>Conflict2 SD = 3.35</td>
<td>Conflict2 PSE = -0.03</td>
<td>RSD score = 3.19</td>
</tr>
</tbody>
</table>
Figure B4 Psychometric functions for each participant with NT. The left box displays unisensory visual (red plus sign) and haptic (blue squares) conditions. The right displays conflict 1 (green upward triangles) and conflict 2 (magenta downward triangle) conditions. RSD scores are included for each participant (see Appendix B2) this score was calculated as the difference between participants PSE in each conflict condition and the MLE prediction.
B4 PSEs in each conflict condition

Figure B5 Measured PSE in conflict 1 (blue dots) and conflict 2 (green squares) and predicted PSEs conflict 1 (blue line) and conflict 2 (green line)
Appendix C

C1 RT data

Experiment 2 and 3

Table C1 Mean of each participant’s median RT (ms) and SD in each condition for Experiments 2 and 3. Each participant’s RT data was adjusted using an outlier removal procedure (Van Selst and Jolicoeur, 1994).

<table>
<thead>
<tr>
<th>RT (ms)</th>
<th>Experiment 2</th>
<th>SOA</th>
<th>Experiment 3</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-30ms</td>
<td>100ms</td>
<td>200ms</td>
</tr>
<tr>
<td>Baseline</td>
<td>850 ± 191</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experiment 4 and 5

Table C2 Mean of each participant’s median RT (ms) and SD in each condition for Experiments 4 and 5. Each participant’s RT data was adjusted using an outlier removal procedure (Van Selst and Jolicoeur, 1994).

### Experiment 4

<table>
<thead>
<tr>
<th></th>
<th>ASC RT (ms)</th>
<th>Baseline</th>
<th>-30ms</th>
<th>100ms</th>
<th>200ms</th>
<th>400ms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>852.30±111</td>
<td>864.50±132</td>
<td>875.11±145</td>
<td>858.56±127</td>
</tr>
<tr>
<td>Cong</td>
<td></td>
<td></td>
<td>937 ± 227</td>
<td>869.28 ± 129</td>
<td>918.06 ± 201</td>
<td></td>
</tr>
<tr>
<td>Incong</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>NT RT (ms)</th>
<th>Baseline</th>
<th>-30ms</th>
<th>100ms</th>
<th>200ms</th>
<th>400ms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>828.20 ± 123</td>
<td>828.56 ± 147</td>
<td>832.62 ± 119</td>
<td>833.32 ± 155</td>
<td>828.94 ± 146</td>
</tr>
<tr>
<td>Cong</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incong</td>
<td></td>
<td></td>
<td>869 ± 128</td>
<td>860.91 ± 167</td>
<td>872.18 ± 137</td>
<td>826.53 ± 149</td>
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</tbody>
</table>

### Experiment 5

<table>
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<tr>
<th></th>
<th>ASC RT (ms)</th>
<th>Baseline</th>
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<th>21cm</th>
<th>42cm</th>
<th>42cm_opp</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>974.97 ± 235</td>
<td>947.47 ± 231</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cong</td>
<td></td>
<td>934.73 ± 204</td>
<td>918.90 ± 213</td>
<td>952.53 ± 210</td>
<td>1004.64 ± 258</td>
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</tr>
<tr>
<td>Incong</td>
<td></td>
<td>977.20 ± 239</td>
<td>999.63 ± 299</td>
<td>996.56 ± 238</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>NT RT (ms)</th>
<th>Baseline</th>
<th>0cm</th>
<th>21cm</th>
<th>42cm</th>
<th>42cm_opp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>795.13 ± 158</td>
<td>856.23 ± 166</td>
<td>838.77 ± 157</td>
<td>836.80 ± 163</td>
<td>847.53 ± 885</td>
</tr>
<tr>
<td>Cong</td>
<td></td>
<td>856.23 ± 166</td>
<td>838.77 ± 157</td>
<td>836.80 ± 163</td>
<td>847.53 ± 885</td>
<td></td>
</tr>
<tr>
<td>Incong</td>
<td></td>
<td>901.86 ± 246</td>
<td>900.73 ± 206</td>
<td>875.33 ± 193</td>
<td>884.80 ± 224</td>
<td></td>
</tr>
</tbody>
</table>
Experiment 8

Table C3 RT data for each condition and participant in Experiment 8. Each participant’s RT data was adjusted using an outlier removal procedure (Van Selst and Jolicoeur, 1994).

<table>
<thead>
<tr>
<th></th>
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<th>NT</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RT (ms)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>985.59 ± 242.23</td>
<td>Congruent</td>
<td>989.56 ± 280.87</td>
<td>Far</td>
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<tr>
<td></td>
<td></td>
<td>Incongruent</td>
<td>1037 ± 316.52</td>
<td>959.91 ± 261.78</td>
</tr>
<tr>
<td></td>
<td>893.41 ± 203.84</td>
<td>Congruent</td>
<td>972.50 ± 260.60</td>
<td>Far</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Incongruent</td>
<td>932.78 ± 220.36</td>
<td>931.53 ± 216.92</td>
</tr>
</tbody>
</table>

Experiment 9

Table C4 RT data for participants with ASC and NT in each condition on Experiment 9

<table>
<thead>
<tr>
<th></th>
<th>ASC</th>
<th></th>
<th>NT</th>
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</tr>
</thead>
<tbody>
<tr>
<td>RT (ms)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>924.42 ± 192.69</td>
<td>Congruent</td>
<td>858.50 ± 185.53</td>
<td>Far</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Incongruent</td>
<td>939.39 ± 233.44</td>
<td>840 ± 179.71</td>
</tr>
<tr>
<td></td>
<td>787.12 ± 117.98</td>
<td>Congruent</td>
<td>819.15 ± 155.16</td>
<td>Far</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Incongruent</td>
<td>779.56 ± 141.60</td>
<td>849.63 ± 217.16</td>
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</tr>
</tbody>
</table>
Appendix D

D1 Visual only Procedure
Participants completed a short visual task in which they were required to detect a single or double light flash presented from each of the distractor light positions (0cm, 21cm, 42cm and 42cm_opp). Ten light flashes were presented from each position (five single flashes, five double flashes) in a random order. As in the experimental procedure, the LED was stimulated for 80ms for single flashes and double flashes comprised two single 80ms flashes separated by 120ms. Participants were instructed to focus on a central fixation cross, lifting their toe in response to a single flash and heel in response to double.

A mixed ANOVA [Position (0cm, 21cm, 42cm, 42cm_opp) x Group (ASC, NT)] revealed no significant effect of position (F (3, 96) = 2.19, p = 0.95, ηp² = .064), nor a Group x Position interaction F (3, 96) = .55, p = .648, ηp² = .017).

Figure D1 Mean percentage error to light flashes in each position for participants with ASC and NT. Error bars represent standard error of the mean.
D2 Relationship between CE effects and AQ scores for NT participants

Figure D2 The AQ scores for the NT participants plotted as a function of CE at each SOA (Experiment 4; A) and position (Experiment 5; B). No correlation coefficients reached statistical significance in either Experiment 4 ($r < .33$, $p > .178$), or Experiment 5 ($r < .11$, $p > .678$).
Appendix E

E1 Time series for threshold procedures

Participants that reached 100 trials on threshold procedures in Experiment 6 that reached a step size below 10ms were included in analysis. Time series for these participants are included below.

Figure E1: Time series for participants that reached 100 trials on visual threshold procedure. ASC n = 10, NT n = 8.

Figure E2: Time series for participants that reached 100 trials on auditory threshold procedure. ASC n = 10, NT n = 6.
## E2 Participant demographics

*Table E1 Participant demographics for groups included in final analysis Experiment 6*

### Thresholds

<table>
<thead>
<tr>
<th></th>
<th>ASC</th>
<th>NT</th>
<th>Age</th>
<th>IQ</th>
<th>t (df)</th>
<th>p</th>
<th>t (df)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Visual</strong></td>
<td>n=17</td>
<td>17</td>
<td>31.41 ± 8.50</td>
<td>116.47 ± 9.96</td>
<td>28 ± 6.97</td>
<td>113.43 ± 7.22</td>
<td>1.20</td>
<td>.238</td>
</tr>
<tr>
<td></td>
<td>9.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td><strong>Auditory</strong></td>
<td>n=14</td>
<td>14</td>
<td>29.07 ± 7.89</td>
<td>117.14 ± 10.75</td>
<td>31.12 ± 8.97</td>
<td>112.64 ± 7.53</td>
<td>.67</td>
<td>.510</td>
</tr>
<tr>
<td></td>
<td>7.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tactile</strong></td>
<td>n=17</td>
<td>17</td>
<td>31.41 ± 8.50</td>
<td>116.47 ± 9.96</td>
<td>30.76 ± 8.50</td>
<td>113 ± 7.13</td>
<td>.22</td>
<td>.830</td>
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<tr>
<td></td>
<td>9.96</td>
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</table>

### Multisensory TOJs

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<tr>
<th></th>
<th>ASC</th>
<th>NT</th>
<th>Age</th>
<th>IQ</th>
<th>t (df)</th>
<th>p</th>
<th>t (df)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Visual-auditory</strong></td>
<td>n=17</td>
<td>17</td>
<td>31.24 ± 8.59</td>
<td>115.65 ± 9.14</td>
<td>31.06 ± 8.71</td>
<td>112.39 ± 7.39</td>
<td>.08</td>
<td>.936</td>
</tr>
<tr>
<td><strong>Visual-tactile</strong></td>
<td>n=18</td>
<td>18</td>
<td>31 ± 8.43</td>
<td>116.56 ± 9.67</td>
<td>31.06 ± 8.71</td>
<td>112.39 ± 7.39</td>
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<td>.985</td>
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<tr>
<td><strong>Tactile-auditory</strong></td>
<td>n=17</td>
<td>17</td>
<td>31.59 ± 8.29</td>
<td>117 ± 9.78</td>
<td>31.06 ± 8.71</td>
<td>112.39 ± 7.39</td>
<td>.19</td>
<td>.854</td>
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<tr>
<td></td>
<td>8.29</td>
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</tr>
</tbody>
</table>
E3 Individual Psychometric function for bimodal TOJs from Experiment 6

ASC 1
avPSE = 52.46
vtPSE = -27.86
taPSE = -35.5655
avJND = 35.0476
vtJND = 28.1068
taJND = 29.6918

ASC 2
avPSE = 9.57
vtPSE = 39.5
taPSE = -21.26
avJND = 152.66
vtJND = 121.49
taJND = 45.20

ASC 3
avPSE = -31.16
vtPSE = 6.32
taPSE = -24.69
avJND = 109.70
vtJND = 66.36
taJND = 86.64
ASC 4
avPSE = -99.16
vtPSE = 59.44
taPSE = 69.98
avJND = 148.69
vtJND = 95.69
taJND = 81.51

ASC 5
avPSE = 92.47
vtPSE = 27.01
taPSE = 4.12
avJND = 173.19
vtJND = 150.74
taJND = 91.89

ASC 6
avPSE = 19.58
vtPSE = -18.19
taPSE = -5.72
avJND = 45.88
vtJND = 104.01
taJND = 19.12
ASC 7
avPSE = -37.88
vtPSE = 66.02
taPSE = -9.50
avJND = 45.96
vtJND = 80.96
taJND = 36.25

ASC 8
avPSE = 65.49
vtPSE = 11.23
taPSE = -13.11
avJND = 118.76
vtJND = 76.60
taJND = 149.33

ASC 9
avPSE = 264.61
vtPSE = 45.86
taPSE = 5.10
avJND = 299.79
vtJND = 87.33
taJND = 82.27
ASC 10
avPSE = -38.33
vtPSE = 67.07
taPSE = -303.53
avJND = 211.19
vtJND = 179.19
taJND = 423.28

ASC 11
avPSE = 25.13
vtPSE = -24.30
taPSE = 13.20
avJND = 20.71
vtJND = 30.64
taJND = 57.05

ASC 12
avPSE = -38.67
vtPSE = -44.29
taPSE = -12.25
avJND = 143.25
vtJND = 79.14
taJND = 96.28
ASC 13
avPSE = -27.75
taPSE = 31.42
avJND = 28.07
taJND = 54.02

ASC 14
avPSE = 129.04
vtPSE = -130.48
taPSE = 33.69
avJND = 157.68
taJND = 72.42

ASC 15
avPSE = 15.44
vtPSE = -36.01
taPSE = -13.85
avJND = 3.53
taJND = 18.85
Figure E3 Psychometric functions, JND, and PSE for each participant with ASC for auditory-visual pairings (red crosses), visual-tactile pairings (green circles) and tactile-auditory pairings (black crosses).
NT4
avPSE = 55.08
vtPSE = -6.90
taPSE = -26.91
avJND = 84.51
vtJND = 32.53
taJND = 37.31

NT5
avPSE = 20.11
vtPSE = -59.55
taPSE = -31.54
avJND = 112.29
vtJND = 76.88
taJND = 121.79

NT6
avPSE = -30.31
vtPSE = 47.67
taPSE = -1.84
avJND = 77.75
vtJND = 101.47
taJND = 31.99
NT7
\[ \text{avPSE} = -135.97 \]
\[ \text{vtPSE} = -89.39 \]
\[ \text{taPSE} = -158.05 \]
\[ \text{avJND} = 156.96 \]
\[ \text{vtJND} = 114.49 \]
\[ \text{taJND} = 126.71 \]

NT8
\[ \text{avPSE} = 32.75 \]
\[ \text{vtPSE} = -38.97 \]
\[ \text{taPSE} = 17.96 \]
\[ \text{avJND} = 174.81 \]
\[ \text{vtJND} = 74.50 \]
\[ \text{taJND} = 209.74 \]

NT9
\[ \text{avPSE} = 91.33 \]
\[ \text{vtPSE} = -18.42 \]
\[ \text{taPSE} = -25.72 \]
\[ \text{avJND} = 148.62 \]
\[ \text{vtJND} = 180.15 \]
\[ \text{taJND} = 80.39 \]
NT10
avPSE = -83.51
vtPSE = 24.48
taPSE = -1.67
avJND = 81.50
vtJND = 75.64
taJND = 104.95

NT11
avPSE = 91.33
vtPSE = -18.42
taPSE = -25.72
avJND = 148.62
vtJND = 180.15
taJND = 80.39

NT12
avPSE = 20.34
vtPSE = 42.36
taPSE = -101.52
avJND = 90.50
vtJND = 62.47
taJND = 99.54
NT13
avPSE = 14.44
vtPSE = -10.07
taPSE = 13.19

avJND = 66.67
vtJND = 48.87
taJND = 56.13

NT14
avPSE = 39.05
vtPSE = -22.88
taPSE = -12.93

avJND = 62.21
vtJND = 73.36
taJND = 41.63

NT15
avPSE = 9.50
vtPSE = 13.31
taPSE = 72.18

avJND = 138.76
vtJND = 64.10
taJND = 133.04
Figure E4 Psychometric functions, JND and PSE for each participant with NT for auditory-visual pairings (red crosses), visual-tactile pairings (green circles) and tactile-auditory pairings (black crosses).
E4 Multiple regressions exploring relationships with autistic traits for NT participants

A multiple regression was calculated to explore the relationship between NT participant self-reported autistic traits using the AQ and the JNDs for each bimodal pairing. JNDs did not significantly predict autistic traits (F (3, 15) = .88, p = .477). A summary of the regression data is included in Table E2.

Table E2 Regression data comparing multisensory temporal sensitivity and autistic traits

<table>
<thead>
<tr>
<th></th>
<th>R² adjusted</th>
<th>β</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory-Visual JND</td>
<td>.02</td>
<td>.16</td>
<td>.50</td>
<td>.623</td>
</tr>
<tr>
<td>Visual-Tactile JND</td>
<td>.48</td>
<td>1.59</td>
<td></td>
<td>.138</td>
</tr>
<tr>
<td>Tactile-Auditory JND</td>
<td>&gt;.01</td>
<td>.01</td>
<td></td>
<td>.991</td>
</tr>
</tbody>
</table>

A multiple regression was calculated to explore the relationship between NT participant self-reported autistic traits using the AQ and the PSEs for each bimodal pairing. PSEs did not significantly predict autistic traits (F (3, 15) = .73, p = .553). A summary of the regression data is included in Table E3.

Table E3 Regression data comparing PSE in each condition and autistic traits

<table>
<thead>
<tr>
<th></th>
<th>R² adjusted</th>
<th>β</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory-Visual PSE</td>
<td>.06</td>
<td>.33</td>
<td>.81</td>
<td>.429</td>
</tr>
<tr>
<td>Visual-Tactile PSE</td>
<td>.09</td>
<td>.30</td>
<td></td>
<td>.778</td>
</tr>
<tr>
<td>Tactile-Auditory PSE</td>
<td>.60</td>
<td>1.38</td>
<td></td>
<td>.192</td>
</tr>
</tbody>
</table>
Appendix F

F1 Individual psychometric functions for visual- tactile TOJs on Experiment 7

ASC 1
nearPSE = 41.90
farPSE = -38.14
nearJND = 160.25
farJND = 106.15

ASC 2
nearPSE = -24.57
farPSE = -14.17
nearJND = 35.79
farJND = 44.12

ASC 3
nearPSE = 65.14
farPSE = 62.84
nearJND = 103.53
farJND = 102.96

ASC 4
nearPSE = 3.68
farPSE = 20.10
nearJND = 100.05
farJND = 85.32
ASC 5
nearPSE = 85.06
farPSE = 91.50
nearJND = 183.95
farJND = 208.94

ASC 6
nearPSE = -39.26
farPSE = -17.07
nearJND = 71.38
farJND = 56.63

ASC 7
nearPSE = -20.32
farPSE = -9.85
nearJND = 38.49
farJND = 49.43

ASC 8
nearPSE = -34.58
farPSE = 5.45
nearJND = 112.97
farJND = 99.30

ASC 9
nearPSE = 76.03
farPSE = 70.72
nearJND = 113.16
farJND = 51.22
ASC 10
nearPSE = 12.94
farPSE = -3.09
nearJND = 73.56
farJND = 38.88

ASC 11
nearPSE = 49.44
farPSE = -0.68
nearJND = 51.31
farJND = 32.83

ASC 12
nearPSE = -3.11
farPSE = 17.51
nearJND = 8.92
farJND = 11.45

ASC 13
nearPSE = -32.62
farPSE = -7.24
nearJND = 54.38
farJND = 73.26

ASC 14
nearPSE = 36.23
farPSE = 27.53
nearJND = 77.02
farJND = 65.82
Figure F1 Psychometric function for each participant with ASC on Experiment 7 including JNDs and PSE. Responses in the near condition are given by magenta crosses, the far condition by green circles.
**NT 1**
- nearPSE = -16.48
- farPSE = -28.49
- nearJND = 70.89
- farJND = 53.02

**NT 2**
- nearPSE = 25.09
- farPSE = -12.97
- nearJND = 63.70
- farJND = 56.06

**NT 3**
- nearPSE = 12.58
- farPSE = -7.37
- nearJND = 39.01
- farJND = 44.58

**NT 4**
- nearPSE = 21.66
- farPSE = 65.81
- nearJND = 42.32
- farJND = 56.07

**NT 5**
- nearPSE = -5.91
- farPSE = -11.88
- nearJND = 56.52
- farJND = 50.42
NT 6
nearPSE = 29.29
farPSE = 48.13
nearJND = 59.76
farJND = 51.03

NT 7
nearPSE = 47.95
farPSE = 19.42
nearJND = 107.12
farJND = 86.96

NT 8
nearPSE = 18.25
farPSE = 3.82
nearJND = 60.35
farJND = 33.20

NT 9
nearPSE = 61.21
farPSE = 15.86
nearJND = 99.23
farJND = 79.64

NT 10
nearPSE = 101.57
farPSE = 39.02
nearJND = 147.44
farJND = 64.77
NT 11
nearPSE = -38.70
farPSE = 1.26
nearJND = 125.49
farJND = 191.09

NT 12
nearPSE = 42.63
farPSE = 15.22
nearJND = 57.64
farJND = 31.78

NT 13
nearPSE = -49.90
farPSE = -46.86
nearJND = 79.83
farJND = 109.25

NT 14
nearPSE = 35.41
farPSE = 31.12
nearJND = 60.03
farJND = 46.63

NT 15
nearPSE = 5.35
farPSE = 9.83
nearJND = 59.17
farJND = 61.70
Figure F2 Psychometric function for each NT participant on Experiment 7 including JND and PSE in each condition. Responses in the near condition are given by magenta crosses, the far condition by green circles.
F2 Analysis of congruency effect data

Experiment 8
A mixed ANOVA [Position (Near, Far) x Group (ASC, NT)] revealed a significant effect of position $F(1, 31) = 4.61, p = .040, \eta_p^2 = .13$ indicating that the size of the CE was significantly larger in the near condition than the far condition (near = 15.51% ± 15.52; far = 11.51% ± 17.56). The interaction between Group and Position was not statistically significant $F(1, 31) = 2.00, p = .166, \eta_p^2 = .061$.

![Figure F3 Congruency effect (% error) in each position for participants with ASC (dark grey) and NT (light grey). The congruency effect is calculated by deducting the error rate in the incongruent condition from the congruent. Asterisk denote a significant CE (Bonferroni corrected $\alpha = .025$) Error bars represent SEM.](image-url)
Experiment 9
A mixed ANOVA [Position (near, far) x Group (ASC, NT)] revealed a significant effect of position F (1, 29) = 10.78, p = .003, ω² = .271) indicating that the size of the CE was significantly larger in the near condition than the far condition (mean near = 32.03 ± 16.98; mean far = 21.95 ± 16.33). The interaction between Group and Position was not statistically significant F (1, 29) = .03, p = .872, ω² < .01).

Figure F5 Visual congruency effect (% error) in each position for participants with ASC (dark grey) and NT (light grey). The congruency effect is calculated by deducting the error rate in the incongruent condition from the congruent. Asterisk denote a significant CE (Bonferroni corrected α = .025) Error bars represent SEM.
F3 Pilot test of visual congruency task
The aim of this experiment was to create a visual analogue of our spatial CCT (Experiments 3, 5, 8) to investigate whether individuals with ASC showed issues spatial modulating distracting light flashes in the unisensory visual modality.

It was anticipated that NT participants would display a greater visual congruency effect for stimuli presented close to the target light (near) than a position in the opposite hemispace (far).

Method

Participants
16 participants (one male, two left handed) with an average age of 19.43 years ± 1.84 were recruited from the student population at the University of Manchester and were compensated with course credit.

Apparatus, procedure and analysis were identical to Experiment 9. Testing took approximately 30 minutes.

Results
There was a significant interference effect in both the near and far conditions. Critically, the interference effect was significantly larger in the near condition than in the far condition, indicating spatial modulation of incongruent distractors. Paired sample t-tests (Bonferroni corrected α = .013) were conducted to compare the error rate in each condition with baseline performance. Participants produced an error rate that was significantly greater than baseline for incongruent distractors presented in the near condition (t (15) = 11.74, p < .001, d = 2.07) and the far condition (t (15) = 3.46, p = .003, d = .85). No other differences reached statistical significance (t < 3.46, p > .024,). A paired sample t-tests revealed the interference effect was significantly larger in the near condition than the far condition (t (15) = 3.20, p = .006, d = .98).
Figure F4 Mean error rate for congruent (diamonds) and incongruent trials (squares) in each position. Mean error rate in the green LED only baseline condition is represented for each group by the dotted line. Asterisks denote a significant difference from baseline (Bonferroni corrected, $\alpha = .013$). Error bars denote within participants confidence intervals (Cousineau, 2005).

**Discussion**

In the current experiment we aimed to explore the effect of judgements about a green visual target, when presented with task-irrelevant red visual distractors. These distractors were presented in a position close (0cm) or far (42cm) from the target. The error rate in response to incongruent distractors presented both near and far from the target were significantly greater than baseline performance. The interference effect, calculated as the error rate in response to incongruent distractors in each condition, was significantly larger in the near condition than the far condition. The spatial modulation of visual distractors on a visual target was therefore captured in the present experiment. This experiment was then repeated in Experiment 9 to investigate differences in the spatial modulation of visual targets in a group of adults with ASC and matched NT controls.