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A Psychophysical Assessment of Multisensory Processing and Multiple Object Tracking in Autism Spectrum Disorders

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Résumé

Les troubles du spectre autistique (TSA) sont actuellement caractérisés par une triade d'altérations, incluant un dysfonctionnement social, des déficits de communication et des comportements répétitifs. L'intégration simultanée de multiples sens est cruciale dans la vie quotidienne puisqu'elle permet la création d'un percept unifié. De façon similaire, l'allocation d'attention à de multiples stimuli simultanés est critique pour le traitement de l'information environnementale dynamique. Dans l'interaction quotidienne avec l'environnement, le traitement sensoriel et les fonctions attentionnelles sont des composantes de base dans le développement typique (DT). Bien qu'ils ne fassent pas partie des critères diagnostiques actuels, les difficultés dans les fonctions attentionnelles et le traitement sensoriel sont très courants parmi les personnes autistes. Pour cela, la présente thèse évalue ces fonctions dans deux études séparées.

La première étude est fondée sur la prémisse que des altérations dans le traitement sensoriel de base pourraient être à l'origine des comportements sensoriels atypiques chez les TSA, tel que proposé par des théories actuelles des TSA. Nous avons conçu une tâche de discrimination de taille intermodale, afin d'investiguer l'intégrité et la trajectoire développementale de l'information visuo-tactile chez les enfants avec un TSA (N = 21, âgés de 6 à18 ans), en comparaison à des enfants à DT, appariés sur l'âge et le QI de performance. Dans une tâche à choix forcé à deux alternatives simultanées, les participants devaient émettre un jugement sur la taille de deux stimuli, basé sur des inputs unisensoriels (visuels ou tactiles) ou multisensoriels (visuo-tactiles). Des seuils différentiels ont évalué la plus petite différence à laquelle les participants ont été capables de faire la discrimination de taille. Les enfants avec un TSA ont montré une performance diminuée et pas d'effet de maturation aussi bien dans les conditions unisensorielles que multisensorielles, comparativement aux participants à DT. Notre première étude étend donc des résultats précédents d'altérations dans le traitement multisensoriel chez les TSA au domaine visuo-tactile.

Dans notre deuxième étude, nous avions évalué les capacités de poursuite multiple d'objets dans l'espace (*3D-Multiple Object Tracking (3D-MOT)*) chez des adultes autistes (N = 15, âgés de 18 à 33 ans), comparés à des participants contrôles appariés sur l'âge et le QI, qui devaient suivre une ou trois cibles en mouvement parmi des distracteurs dans un environnement de réalité virtuelle. Les performances ont été mesurées par des seuils de vitesse, qui évaluent la plus grande vitesse à laquelle des observateurs sont capables de suivre des objets en mouvement. Les individus autistes ont montré des seuils de vitesse réduits dans l'ensemble, peu importe le nombre d'objets à suivre. Ces résultats étendent des résultats antérieurs d'altérations au niveau des mécanismes d'attention en autisme quant à l'allocation simultanée de l'attention envers des endroits multiples.

Pris ensemble, les résultats de nos deux études révèlent donc des altérations chez les TSA quant au traitement simultané d'événements multiples, que ce soit dans une modalité ou à travers des modalités, ce qui peut avoir des implications importantes au niveau de la présentation clinique de cette condition.

Mots-clés: Troubles du spectre autistique, traitement multisensoriel, traitement visuo-tactile, développement, attention, 3D-MOT

Abstract

Autism spectrum disorders (ASD) are currently characterized by a triad of impairments including social dysfunction, communication deficits and perseverative behaviours. The simultaneous integration of multiple senses is crucial in everyday life as it allows for the creation of a unified percept. Similarly, the allocation of attention to multiple events at the same time is critical in the processing of dynamic environmental information. In daily interactions with the environment, both sensory processing as well as attentional functions are building blocks to typical development (TD). Although not part of the current diagnostic criteria, difficulties with attention functions and sensory processing are very common among autistic persons. The present thesis therefore examined both these functions in two separate studies.

The first study is based on the premise that alterations in basic sensory processing might underlie atypical sensory behaviours in ASD, as proposed by current theories of ASD. We conceived a cross-modal size discrimination task to assess the integrity and developmental course of visuo-tactile information in children with ASD (N = 21, aged 6-18 years), compared to age- and performance IQ-matched children with TD. In a simultaneous two-alternative forced-choice task, participants were asked to make a judgement on the size of two stimuli, based on unisensory (visual or tactile) or multisensory (visuo-tactile) inputs. Difference thresholds evaluated the smallest difference at which participants were capable to discriminate size. Children with ASD showed diminished performance and no maturational effects in both unisensory and multisensory conditions, compared to TD participants. Our first study therefore extends previous results of alterations in multisensory processing in ASD to the visuo-tactile domain.

In our second study, we evaluated 3D-Multiple Object Tracking (3D-MOT) capacities in autistic adults (*N* = 15, aged 18-33 years), compared to age- and IQ-matched control participants, who were asked to track one or three moving targets amongst a set of distracters in a virtual reality environment. Performances were measured based on speed thresholds, which evaluates the greatest speed at which observers are capable of successfully tracking moving objects. Autistic individuals displayed overall reduced speed thresholds, whatever the number of spheres to track. These findings extend previous results of altered attention mechanisms in autism with regards to the simultaneous allocation of attention to multiple areas.

Together, the findings of our two studies reveal alterations in ASD with regards to the processing of multiple events at the same time, be it within one modality or across modalities, which may have important implications for the clinical presentation of this condition.

Keywords: Autism spectrum disorders, multisensory processing, visuo-tactile processing, development, attention, 3D-MOT

Table of contents

List of tables

Article 1

Article 2

List of figures

Article 1

Article 2

List of abbreviations

3D: 3 Dimensions
AD: Autistic disorder
APA: American Psychiatric Association
ASD: Autism spectrum disorder
DSM: Diagnostic and statistical manual of mental disorders
fMRI: Functional magnetic resonance imaging
LOC: Lateral occipital complex
MEG: Magnetoencephalography
MOT: Multiple Object Tracking
MSI: Multisensory integration
PET: Positron emission tomography
PIQ: Performance intelligence quotient
STS: Superior temporal sulcus
TD: Typical development
VIQ: Verbal intelligence quotient
WCC: Weak central coherence

To the families of autistic children,
respectfully.

Because autism does not only change
one life, but many. Because I have
utmost admiration for those who show
courage, perseverance and love in the
face of a phenomenon that remains
to be fully understood.

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“ Know thyself ” - Socrates

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Chapter 1. Introduction

"The world is a sensory place. Sensation is everywhere. Not only are people sensory beings, the world is a sensory place as well. The world around us makes sounds, provides textures, offers tastes and smells, and contains a myriad things to see. We use sensory words to describe all of the physical characteristics of our homes, workplaces, parks, restaurants, stores, and any other setting. For example, a store might be described as bright, noisy, and crowded, reflecting the visual, auditory, and touch sensory systems." (Dunn, 2007, p. 17)

This description by Dunn summarizes well the crucial role of sensory information in our lives. It also attests to the importance of studying sensory behaviours. If it was just us people, who were sensory beings. Or just the environment that generated sensory experiences. No, sensation is everywhere. Which means, we cannot escape from it. We are surrounded by it. Whether we like it or not. In the same way, multiple events are happening, in multiple sensory modalities and within the same modality. Thereafter, we have to process it all, integrate it. It may seem like an obvious thing to do, like an automatic thing to do. We usually don't think about it. In our daily activities, information from multiple sensory modalities seems to merge with fluency. For instance, driving a car involves the synthesis of visual (seeing the road, paying attention to other cars and pedestrians), auditory (hearing the car engine), somatosensory (feeling the steering wheel) and motor (depressing the gas pedal) activity (Molholm et al., 2002). However, what happens if this process does not come as easily to a person? We could only imagine, and hardly so, what the repercussions might be on this person's approach to everyday life, as reported by this autistic man: "Sometimes the channels get confused, as when sounds come through as color. Sometimes I know that something is coming in somewhere, but I can't tell right away what sense it's coming through." (Cesaroni & Garber, 1991, p. 305).

Autism is a very early onset neurodevelopmental disorder that is characterized by a number of behavioural symptoms, including deficits in communication and social interaction, as well as atypical sensory reactions and interests. Autistic individuals experience difficulties with sensory input from the environment, notably involving input from several modalities (e.g., Cesaroni & Garber, 1991; Grandin & Scariano, 1986) that may lead to confusing and distorted perceptions, and hence result in adaptive behaviours such as social withdrawal. Until now, there is no empirical explanation for these unusual sensory reactions, but recent reviews (Bahrick & Todd, 2012; Iarocci & McDonald, 2006; Waterhouse, Fein, & Modahl, 1996) suggest that an alteration in the integration of sensory input from multiple sensory modalities might at least explain some of the atypical sensory-perceptual behaviours observed in autism. Considering that interaction between individuals and the world around them is mediated entirely through their sensory domains (Kenet, 2011) and the development of perception is founded on a growing child's abilities to attend to and spatially and temporally integrate multiple sources of input (Iarocci & McDonald, 2006), we can easily expect the result to be anomalous if things go awry somewhere at this stage.

In autism research, characterizing early markers and the possible nature of developmental cascades leading to its behavioural expression and increasing symptom severity is currently an important challenge (Bahrick & Todd, 2012). Rising up to this challenge is crucial for the early identification of children at risk for developing an autism spectrum disorder (ASD) and the conception of novel interventions. Recent research has made it clear that future efforts should focus on identifying impairments in fundamental skills that emerge and develop early (Rogers, 2009), and that are "primary" areas of impairment potentially affecting a variety of later-developing symptoms (Zwaigenbaum, Bryson, Rogers, Roberts, Brian, & Szatmari, 2005). Given the critical roles of multisensory processing and attention functions in the typical emergence of social skills, such as social orienting and joint attention, areas well known to be impaired in autism (Mundy & Burnette, 2005), anomalies in these processes may be considered as primary areas of impairment. In the daily interaction with the environment, both sensory processing as well as attentional functions are building blocks to typical development (TD). Although not part of the current diagnostic criteria, difficulties with attention functions and sensory processing are very common among children with ASD. It seems that in order to better comprehend atypical behavioural expression, we need to understand how information is processed at the input level (i.e. at the sensory processing stage), and further how this input level is modulated through attention functions. For this reason, we were highly interested in studying both these functions in two separate studies in ASD. Our general objective was to obtain a better understanding of how individuals with ASD process and integrate basic multisensory information (first study) and how they are able to allocate their attention to multiple areas at the same time (second study), compared to typical participants. Finally, applying a developmental perspective being critical to understanding developmental disorders (Bahrick & Todd, 2012), we additionally evaluated the development of sensory processing skills in our first study.

Chapter 2. Multisensory Processing

2.1. Multisensory Integration

During the past decade there has been an increasing shift of focus away from the study of the senses in isolation and towards an understanding of how the brain integrates the input provided by the different sensory modalities. This multisensory perspective on human sensory perception has evolved partly as a consequence of developments in both technology and sensory neurophysiology (Calvert & Thesen, 2004). With the introduction of novel brain imaging techniques, such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) emerged the study of global brain function. Research could now focus on how systems interacted, rather than how they behaved in isolation (Calvert & Thesen, 2004). At the same time, a growing body of literature attested to our knowledge of the mechanisms involved in the primary sensory systems. However, what emerged was the realization that a precise and detailed understanding of the components of the perceptual system was necessary but not sufficient (Iarocci & McDonald, 2006). A complete understanding of our perceptual systems therefore would require the consideration of how each sense was modulated by or integrated with input arriving from different sensory channels (Calvert & Thesen, 2004).

The evolutionary basis of these multisensory abilities is obvious. The coexistence of different sensory systems significantly enhances an organism’s likelihood of survival, as it is provided with many sources of input that can operate simultaneously or substitute for one another when necessary (e.g., in the dark, auditory and tactile cues must substitute for vision) (Stein & Meredith, 1993). At the same time, each sense provides qualitatively distinct subjective impressions of the world and hence provides the person with a singular insight of his environment (Stein & Meredith, 1993). Colour and pitch, for example, have no counterparts in somatosensation, and there is no equivalent of tickle in audition or vision (Calvert, 2001). Despite this remarkable disparity of these sensations, we are nevertheless able to maintain a coherent and unified perception of our surroundings (Calvert, 2001).

Cross-modal capabilities present considerable behavioural advantages. These include the capacity to use sensory information interchangeably, thus maintaining object recognition skills when deprived of a sense, and the ability to combine sensory inputs across modalities can dramatically enhance the detection and discrimination of external stimuli and markedly speed responsiveness (Perrott, Saberi, Brown, & Strybel, 1990; Stein, Meredith, Huneycutt, & McDade, 1989). Amodal information is information that is not specific to a particular sense modality, but can be redundantly recognized across more than one sense (auditory, visual, tactile, proprioceptive). When the same amodal information (e.g., rhythm, tempo, intensity) is concurrently and synchronously available to multiple sensory modalities, this is termed "intersensory redundancy" (Bahrick & Lickliter, 2000), which promotes heightened neural responsiveness as compared with the same information presented to each modality alone (Stein & Meredith, 1993). Further, when information from the different senses is complementary, the cross-modal integration of sensory inputs can provide information about the environment that is unobtainable from any one sense in isolation (O'Hare, 1991). For example, our subjective experience of taste derives from the combination of gustatory and olfactory cues (Calvert, 2001). Although some modality-specific stimulus characteristics may be largely preserved as the brain sorts out the inputs from multiple indices, others may be altered and thus, there is an intertwining of different sensory impressions through which sensory components are altered by and integrated with one another (Stein & Meredith, 1993). Typically, this process happens naturally, all the while acting as a buffer against learning inappropriate associations across senses (Bahrick & Todd, 2012). At other times, this is not the case, as in one of the most intriguing examples of cross-modal interaction. Synaesthesia is a neurologically based condition, in which an involuntary conscious sensation (such as colour) is induced by a stimulus in another modality (such as sound), hence its name "joined sensation". Synaesthesia can occur in normal, healthy populations, in brain-damaged or sensory-deafferented patients, as well as in people who are addicted to hallucinogenic drugs (Grossenbacher & Lovelace, 2001). It is a highly interesting phenomenon in the study of autism, as it is often found to be experienced in this population (O'Neill & Jones, 1997). It is also a great example of a sensory anomaly observed in typical and atypical development, in which the function as a buffer against learning inappropriate associations does not seem to be working properly. For example, a grapheme-color synaesthete makes associations between letters and colours, thus inappropriate experiences are generated in the brain. These associations can serve as a mnemonic aid, if a person learns how to use these merged sensory percepts. However, it could also lead to some form of sensory overload, as it may require extra processing or integration, due to the creation of inappropriate associations. Based on numerous anecdotal reports by individuals with ASD, if we then consider the possibility that many more of these sensory associations occur in the brain of individuals with ASD at any given time and likely at a much higher frequency and intensity, we could imagine why these individuals often struggle during interactions with their environments.

2.2. Multisensory Perceptual Phenomena in Humans

The wealth of phenomenological and psychophysical literature on perceptual systems indicates that there is dynamic interaction and integration among the sensory modalities (Shimojo & Shams, 2001). Similarly, the wealth of literature on issues of task complexity certainly attests to the lack of consensus on one single definition. Levels of task complexity are therefore distinguished here based on the definition most commonly observed in the autism literature, which might not be reflective of our current knowledge in perception research. For the purpose of our research, a task is defined as being a higher-order multisensory integration (MSI) task, as soon as it involves any type of socially relevant aspects or stimuli, including language or any kind of learning or semantic processing. These tasks are often referred to as being more complex in the autism literature. A low-level MSI task and stimuli on the other hand would be a task that measures basic aspects of sensory processing, which are independent of language and do not involve any aspects related to communication or social interaction. These tasks are therefore rather termed as being simple in the autism literature. Hereafter are presented a few examples of these two types of tasks and stimuli in the literature of typical human development.

2.2.1. Higher-Order Multisensory Integration

The effects of cross-modal integration are shown under well-designed conditions, revealing notably a number of phenomena during which vision alters other modalities. One example, in which vision alters speech perception, is the McGurk effect (McGurk & MacDonald, 1976). In this classic demonstration based on the perception of spoken syllables, incongruent lip movements induce the misperception of auditory inputs. For example, upon hearing /baba/ but seeing /gaga/, most subjects will report hearing the fused percept /dada/ (McGurk & MacDonald, 1976). Thus, multisensory inputs concerning object identity can be combined to produce a novel perceptual outcome, one that was neither heard nor seen. Further, the spatial location of a sound source can also be drastically influenced by visual stimulation (Shimojo & Shams, 2001). This effect is known as the ‘ventriloquism effect’ (Howard & Templeton, 1966), and is often experienced in daily life, for instance when watching television or movies, where voices are perceived to originate from the actors on the screen instead of the speakers located next to the screen, and this despite a potentially large spatial discrepancy between the two (Shimojo & Shams, 2001).

2.2.2. Low-Level Multisensory Integration

With regards to a lower level of integration, it was shown that perceived size of an object simultaneously seen and felt was dominated by vision when subjects looked at the object through a cylinder lens that made a square look like a rectangle and hence created a conflict between visual and haptic information (Rock & Victor, 1964). This phenomenon of visual dominance was subsequently called ‘visual capture’ (Ernst &

Bulthoff, 2004). Although the best-known cross-modal effects are those of vision influencing other modalities, recent findings suggest that visual perception can also be altered by other modalities. Shams and collaborators reported an illusion known as the illusory flash effect where a single visual flash can be perceived as two flashes if it is accompanied by two (rather than one) closely successive sounds (Shams, Kamitani, & Shimojo, 2000). This illusion was found to occur in healthy observers despite important differences in contrast, form and texture, duration of flash and auditory signals, as well as spatial disparity between the sound and the flash (Shams et al., 2000). Moreover, Sekuler, Sekuler, & Lau (1997) showed that sound can alter the visual perception of motion by demonstrating that sound at or near the point of coincidence of two moving discs promotes perception of ‘bouncing’. Finally, it has been demonstrated that auditory noise facilitates not only visual, but also tactile and proprioceptive sensations (Lugo, Doti, & Faubert, 2008), thus extending a phenomenon called stochastic resonance (Moss, Ward, & Sannita, 2004) to humans, whereby the addition of noise can improve the detection of weak stimuli.

2.3. Cross-modal Integration of Form Information

Object properties (e.g., size and shape) are perceived through multiple sensory modalities. For example, when judging an object’s size, both the visual and the haptic modalities can provide information (Helbig & Ernst, 2007). These multiple sensory inputs are generally integrated into a unified percept. Hence, cross-modal sensory integration of form information is a crucial part of perception with high adaptive value. Size is a fundamental aspect of form perception that can be studied by psychophysical methods. Therefore, we used a cross-modal size discrimination task, in order to investigate multisensory integration in ASD and TD. This multisensory task does not only constitute a prerequisite for higher order processes such as object recognition, but in itself is a very ecological task.

When different perceptual signals of the same physical property are integrated, such as an object's size, which can be seen and felt, the brain sorts out the redundant sources of information across sensory modalities to generate the most reliable estimate (Ernst & Banks, 2002). The nervous system then integrates noisy sensory information from multiple sensory modalities, so that the variance of the final multimodal estimate is reduced to its maximum (Helbig & Ernst, 2007). A number of studies used real objects (e.g., plastic rectangles, wooden blocks) to investigate integration of visual and haptic size information (Hershberger & Misceo, 1996; McDonnell & Duffett, 1972; Miller, 1972; Power & Graham, 1976; Rock & Victor, 1964). In these studies, conflicts were created between visually and haptically specified sizes. This was mostly done by means of a lens that optically distorts the visual image along one axis while the tactile object is unaffected (Helbig & Ernst, 2007). Some studies (Miller, 1972; Power & Graham, 1976; Rock & Victor, 1964) observed that vision dominates the bimodal size percept, whereas others observed a considerable contribution of touch to the bimodal percept (Hershberger & Misceo, 1996; McDonnell & Duffett, 1972). While several studies have shown that adults integrate visual and haptic information in a statistically optimal fashion (Ernst & Banks, 2002), others looked at the development of cross-modal integration and showed that prior to 8 years of age, integration of visual and haptic spatial information is less than optimal, with either vision or touch dominating totally (Gori, Del Viva, Sandini, & Burr, 2008). For size discrimination, Gori et al. (2008) found that haptic information dominates in determining both perceived size and discrimination thresholds, whereas for orientation discrimination, vision dominates. By 8-10 years, the integration becomes statistically optimal, like adults. In our experiment, we decided to assess cross-modal size discrimination in autistic and typically developing children from 6 years on to the end of adolescence (18 years). Our study was similar to Gori et al. (2008), in that we used a measure of size discrimination, however different in that we opted for the simultaneous (vs. successive) presentation of stimuli and against a standard stimulus. We therefore chose to study children from a young age on (6 years), as they did, in order to obtain a complete picture of the development of these processes on our task. We did expect typical developing children to show maturation over time, most likely before the age of 10, based on these previous findings in typical development. Since we knew that around this age size discrimination capacities are close to being fully developed, we proposed to evaluate if this integration was as optimal in children with ASD or if it was rather delayed or even completely altered compared to TD. Thus, as we assumed that these abilities might develop differently in autistic children, we decided to study these capacities across development, in order to allow for a comprehensive understanding of the maturity of these processes.

2.4. Development of Multisensory Processing Skills in Typical Development

In order to understand atypical development, we need to know what happens in typical development, so as to be able to see when and where things might go awry. While adults are adept at selectively attending to multimodal events that are relevant to their present situation (e.g., the face and voice of a person speaking), this is far more challenging for infants (Bahrick & Todd, 2012). A brief review of the development of multisensory processing skills in typical development is presented hereafter, including a summary of the two predominant theories concerned with the development of these abilities, as well as an account of the developmental timing of these skills.

2.4.1. Integration versus Differentiation View

Two opposite theoretical positions, the integration view and the differentiation view, have offered their position on the development of cross-modal abilities, both with a long history (Lickliter & Bahrick, 2004). Globally, the *integration view* proposes that the different sensory modalities function as separate sensory systems during the initial stages of postnatal development and gradually become integrated during the course of development through the infant's activity and repeated experience with simultaneous information provided to the different sensory channels (Birch & Lefford, 1963; Freides, 1974; Piaget, 1952). The *differentiation view* on the other hand suggests that a primitive unity of the senses exists early in development, and as the infant develops, the sensory modalities differentiate from one another (Bower, 1974; Gibson, 1969; Marks, 1978). According to this view, the senses are initially unified, and infants differentiate finer and more complex multimodal relationships through their experience over the course of development. Although some controversy remains around these opposite positions (Bushnell, 1994; Maurer, 1993), the current view argues against an all-or-none dichotomy between integration and differentiation views of perceptual development (Lickliter & Bahrick, 2004). This mounting evidence that the senses are not as segregated as initially thought and that both the differentiation and integration processes are involved in perceptual development is of utmost importance in the study of autism, as one of these mechanisms might not be unfolding adequately in the development of these children and explain some of their atypical behaviours.

2.4.2. Developmental Timing of Multisensory Processing Skills

That information can be transferred from modality to modality at very early stages of development is evident from the observation that minutes after birth babies exhibit good visual-tactile cross-modal transfer (Kaye & Bower, 1994) and are capable to imitate certain facial expressions without visual feedback of their own expressions (Meltzoff & Moore, 1977, 1983). Transfer from touch to vision was observed in newborn babies for shape (Streri & Gentaz, 2004) and in 1-month-old infants for texture (with an oral-tactual familiarisation) (Meltzoff & Borton, 1979). Touch-to-vision transfer of shape was also observed at 2 months (Streri, 1987) and 6 months of age (Rose, Gottfried, & Bridger, 1981a; Ruff & Kohler, 1978) and was more developed by 1 year of age (Gottfried, Rose, & Bridger, 1977; Rose, Gottfried, & Bridger, 1981b, 1983), whereas cross-modal perception involving vision and hearing was observed in 4 ½ month old infants who were able to detect the correspondence between auditorially and visually perceived speech (Kuhl & Meltzoff, 1982).

However, most of these studies did not measure integration per se, but the capacity to compare information from different senses. Thus, it is rather the ability to detect *equivalence* across sensory modalities that occurs early in development (Lewkowicz & Lickliter, 1994). When looking at integration per se, we find that some basic visual and tactile properties, such as contrast sensitivity and acuity, reach near-adult levels within the first year of life (Streri, 2003), whereas other attributes, such as form (Kovacs, Kozma, Feher, & Benedek, 1999), motion perception (Ellemberg, Lewis, Meghji, Maurer, Guillemot, & Lepore, 2003), and visual or haptic recognition of 3D objects (Rentschler, Juttner, Osman, Muller, & Caelli, 2004), continue to develop through the school years until 8-14 years of age (Gori et al., 2008).

2.5. Cross-modal Processing in the Brain

Modern brain imaging techniques have made it possible to study the neural sites and mechanisms underlying cross-modal processing in the human brain. These include anterior portions of the superior temporal sulcus (STS), posterior portions of the STS, parietal cortex, including the ventral and lateral intraparietal areas, and premotor and prefrontal cortex (Calvert & Thesen, 2004). Multisensory convergence zones have also been identified in sub-cortical structures, including the superior colliculus, the claustrum, the suprageniculate and medial pulvinar nuclei of the thalamus, and in the amygdaloid complex (Calvert, 2001). However, the precise network of brain areas implicated in any one study is obviously heavily dependent on the experimental paradigms used, the nature of the information being studied and the particular combination of sensory modalities under investigation (Calvert, 2001). For example, Banati et al. (2000) conducted a PET study during a shape matching task and found that the anterior cingulate, inferior parietal lobules and claustrum areas were selectively activated during cross-modal matching. Using fMRI, research showed that the lateral occipital complex (LOC), a cortical area well known to be involved in visual object recognition, was also active during haptic recognition of familiar objects (Amedi, Malach, Hendler, Peled, & Zohary, 2001). Finally, two studies of multisensory integration found evidence of abnormal thalamic activity in autistic individuals. Abnormal thalamic activation was found during auditory-visual integration of emotional cues (Hall, Szechtman, & Nahmias, 2003), and in a study of visuo-motor integration, in which autistic subjects' performance was impaired compared to controls (Muller, Kleinhans, Kemmotsu, Pierce, & Courchesne, 2003).

Chapter 3. Autism Spectrum Disorders

3.1. Diagnostic criteria

Autism Spectrum Disorders are a group of neurodevelopmental disorders of very early childhood that affect as many as 1 in 150 children (Fombonne, Zakarian, Bennett, Meng, & McLean-Heywood, 2006). Despite its neurobiological origin, ASD continues to be diagnosed on the basis of abnormal behavioural manifestations.

3.1.1. Current diagnostic criteria

ASD is currently defined by a triad of impairments including social dysfunction, communication deficits and repetitive and stereotyped behaviours, with initial onset in one of these areas occurring prior to the age of 3 years (4th ed. text rev.; *Diagnostic and statistical manual of mental disorders (DSM-IV-TR);* American Psychiatric Association, 2000). A diagnosis of Autistic Disorder (AD) indicates that impairments are present in each of these symptom domains. However, there is great variability as to the nature and severity of symptoms in ASD (Hus, Pickles, Cook, Risi, & Lord, 2007). Along with variations in clinical presentation within the clusters of the diagnostic triad, other characteristics are observed that are very common in autistic individuals. The current definition does not account for one of the most prevalent features associated with the condition, the unusual sensory reactions and interests observed in many individuals with ASD. The only allusion to sensory symptoms found in the current diagnostic criteria is to sensory *interests*. These are included in the fourth item within the third diagnostic category, 'restricted, repetitive and stereotyped patterns of behavior, interests and activities', which postulates the presence of "persistent preoccupation with parts of objects" (4th ed., text rev.; *DSM-IV-TR;* American Psychiatric Association, 2000). The phrasing of this item indirectly implies the presence of unusual sensory interests. In fact, the item only reflects a very specific sensory interest, for parts of objects, however this is not explicitly stated. Unusual sensory *reactions* are captured nowhere in the current *DSM*. This is surprising given the important role they seem to play in the clinical phenotype of ASD.

3.1.2. Sensory symptoms in ASD

The literature suggests that, although sensory processing atypicalities are not universal or specific to ASD, the prevalence of such abnormalities in ASD is high (Dawson & Watling, 2000). Indeed, sensory behaviours are observed in 69-95% of individuals with ASD (Baker, Lane, Angley, & Young, 2008; Baranek, David, Poe, Stone, & Watson, 2006; Tomchek & Dunn, 2007). Unusual sensory perceptual experiences have been particularly associated with a diagnosis of autism (Dahlgren & Gillberg, 1989; Ornitz, Guthrie & Farley, 1977; Volkmar, Cohen & Paul, 1986). Many of the early clinical descriptions of autism include references to atypical sensory reactions and interests (e.g., DeMeyer, 1976; Wing, 1969) and indeed, unusual sensory responses were included as one of the diagnostic criteria for an assessment of autism in the *DSM-III* (1980) 3rd ed. While sensory anomalies are not a requisite for a diagnosis of ASD, every parent, teacher or clinician, who is or has been in contact with autistic individuals, will attest to the fact that difficulties with sensory processing are central to the challenges associated with the disorder. Similarly, many of the current theories of autism reflect the theme that sensory atypicalities are a core feature of autism and have downstream effects on the development of the perceptual system in autistic individuals (e.g., Happé, 2005; Just, Cherkassky, Keller, & Minshew, 2004; Mottron & Burack, 2001; Bahrick & Todd, 20120). In an extensive review of the literature on sensory dysfunction in autism, Rogers & Ozonoff (2005) reported that despite evidence for the prevalence of sensory symptoms in autism, there is little careful empirical work to support an explanation of the unusual sensory responses often associated with this condition. One hypothesis that gained prominence in the field over the past years proposes abnormality in basic sensory processing to be a common denominator, which may not only underlie atypical sensory behaviours in autism, but also explain some of its core symptoms, such as social withdrawal and perseverative behaviours (Bahrick & Todd, 2012; Baron-Cohen & Belmonte, 2005; Marco, Hinkley, Hill, & Nagarajan, 2011). For this reason, we were particularly interested to study aspects of sensory processing in ASD, in order to further our understanding of its clinical picture, and specifically because these behaviours were still relatively understudied.

3.1.3. Anticipated changes in diagnostic criteria

Anticipated changes in diagnostic criteria in the *Diagnostic and Statistical Manual of Mental Disorders* (5th ed.; *DSM-5*), which are scheduled to be published in 2013, reflect our shift in understanding of the condition. They also seem to come as an answer to a long lasting debate on whether sensory symptoms are a core component of the ASD phenotype, and attest to the relevance of these symptoms in the clinical expression of the disorder. While the *DSM-IV-TR* (2000) 4th ed., text rev. does not include a specific item for sensory symptoms, more specifically for sensory *reactions*, prospective changes in the *DSM 5* (American Psychiatric Association, 2012) dedicate an item to these symptoms, including aspects of both, interests *and* reactions. The new diagnostic criteria for ASD encompass two categories, including deficits in social communication and social interaction, and restricted, repetitive patterns of behaviour, interests, or activities. The last item of the second category explicitly stipulates the presence of: "hyper-or hypo-reactivity to sensory input or unusual interest in sensory aspects of environment; (such as apparent indifference to pain/heat/cold, adverse response to specific sounds or textures, excessive smelling or touching of objects, fascination with lights or spinning objects)" (American Psychiatric Association, 2012).

Further, while the *DSM-IV-TR* (2000) 4th ed., text rev. includes different sub-categories under the umbrella term Pervasive Developmental Disorder (PDD), with Autistic Disorder being one of them, anticipated changes in diagnostic criteria will comprise one single category, called "Autism Spectrum Disorder". Therefore, while our studies have been realized as the *DSM-IV-TR* (2000) 4th ed., text rev. is in effect, the terms *ASD* and *autism* are used interchangeably throughout this thesis (unless otherwise specified), as this has become common practice in the literature and reflects our current understanding of the condition as a spectrum disorder. This notion accounts for the variability in symptom severity and intellectual functioning, as well as the overall heterogeneity in task performance and symptom expression commonly observed within this population. The previously cited item on sensory symptoms in the *DSM 5* (American Psychiatric Association, 2012) is only one example for this, as it encompasses both hyper-or hypo-reactivity to sensory input both in one item.

3.2. Sensory-Perceptual Anomalies in ASD

Evidence of sensory-perceptual anomalies in autism mostly stems from clinical and parental reports as well as from autobiographical accounts by autistic individuals, including unusually intense attention to or avoidance of sensory stimuli from all the modalities (e.g., Grandin, 1992; Williams, 1994). Generally, the reports refer to difficulties in the reception (input) and processing (making sense) of sensory information (Cesaroni & Garber, 1991). Sensory atypicalities in autism occur in multiple forms and across various modalities (Kern, Trivedi, Garver, Grannemann, Andrews, & Savla, 2006). Some individuals with ASD respond in a hypersensitive manner to sensory stimuli, such as being able to hear a distant, approaching noise (e.g., a siren) long before others are able to hear it, or being unable to tolerate a hug or pat on their head. Others may respond in a hyposensitive manner such as failing to orient when someone calls their name, or engaging in self-injurious behaviour without appearing to feel pain (Cascio et al., 2008). Both hyposensitivity and hypersensitivity, soon to be accounted for in the *DSM*, can be noted in the same individual depending on the situation and the sensory modalities involved (Baranek et al., 2006; Dunn, Myles, & Orr, 2002). For instance, fluctuations between hyper- and hyposensitivity could be seen in a child who on one occasion appears to be deaf, whereas on another he reacts to an everyday sound as if it is causing acute pain (Bogdashina, 2003). Overall, anomalies have been described in all main five sensory modalities as well as in kinaesthetic and proprioceptive sensation. According to Harrison & Hare (2004), these include: 1. Hyper and hyposensitivity to stimulation, often fluctuating between the two. 2. Distortions, e.g. depth may be wrongly perceived or still objects perceived as moving. 3. Sensory tune-outs, e.g. sound or vision may suddenly blank out and return. 4. Sensory overload. 5. Difficulties in processing from more than one channel at a time. 6.

Multi- and cross-channel perception similar to synaesthesia. 7. Difficulties in identifying source channel of sensory stimulation.

Heterogeneity observed in sensory symptoms does not only vary within each individual with ASD, but also amongst individuals. O'Neill (1999) therefore suggests: "Learning how each individual autistic person's senses function is one crucial key to understanding that person" (p. 31). Altered sensory thresholds and/or modulation difficulties are hypothesized to result in these unusual sensory features, and often individuals engage in behaviours in an attempt to counteract their effects (Cascio et al., 2008). For example, individuals may respond to hypersensitivity by avoiding situations in which overstimulation is likely to occur. Thus, overwhelming sensory input is often described as an impetus for social withdrawal (Grandin, 2008), whereas individuals with hyposensitivity may engage in “seeking” behaviour to increase their sensory experience (Dunn, 2001). A child may for example resist visiting places of great noise and confusion, such as shopping centres. Similarly, adults with ASD report their discomfort in crowds, where they simultaneously have to face the input of multiple senses and events at the same time.

These behaviours are often a great source of concern and distress for parents and caregivers of autistic children. Understanding their origins better, that is the relationship between these behaviours and underlying sensory perceptual experiences, which give rise to them could help caregivers adapt their responses (Jones, Quigney, & Huws, 2003). While sensory symptoms are often described as a source of distress, both for concerned individuals and caregivers, they are equally found to be a source of fascination and interest, even offering pleasure in some cases (Jones, 2003).

However, autobiographical accounts of unusual sensory experiences, as intriguing and rich in insight they may be, provide only one source of information. They must be considered along with other measures as the reports of one autistic individual may change significantly over time, may not be relevant to others, or may be a merging of self and others' memories about experiences (O'Neill & Jones, 1997). Further, many autistic individuals do not have the cognitive abilities to relate their experience first-hand (Jones, 2003). Therefore, although questionnaires and rating scales may corroborate findings from autobiographical accounts, objective psychophysical approaches are needed to complement this evidence and further the understanding of the underlying processes. Thus, we completed a study, which aimed to systematically investigate sensory processing within and between tactile and visual systems, using a cross-modal size discrimination task.

3.3. Sensory Theories of ASD

Early theories of autism as well as current ones are based on the idea that persons with autism process sensory information in a way that is different from others. Major early theories and a few current ones are presented hereafter.

3.3.1. Early Theories

Initial clinical reports of atypical reactions to sensory stimuli date back to Kanner (1943) who observed unusual attention to parts rather than wholes among individuals he later described as autistic. A few years later, Bergman and Escalona (1949) were the first to offer a sensory hypothesis of autism, suggesting that the child's need to protect himself from the "sensory onslaught" resulted in developmental distortions that eventually led to the symptoms described by Kanner. In the neurological theory of autism, sensory abnormalities occurred in response to a chronic state of over-arousal due to a disturbance in the modulation of arousal level (Hutt, Hutt, Lee, & Ounsted, 1964). At the same time, under-arousal hypotheses have been put forward by Rimland (1964) who suggested a deficit in the reticular activating system that would impair the child’s ability to connect previous experiences with current ones. This was thought to prevent learning and generalization, and contribute to a lack of typical reaction or under-reaction to stimuli. Later on, the perceptual inconstancy theory was developed by Ornitz and Ritvo (1968). Their work further elaborated the earlier over-arousal theories and was built on a model of brainstem dysfunction. The authors suggested five main symptoms to characterize autism. Primary symptoms included abnormalities in perceptual integration and motility patterns, while secondary symptoms involved language, social, and developmental rate abnormalities. According to this perspective, autism was conceptualized as stemming from abnormal states of arousal due to brainstem abnormalities, resulting in fluctuating states of both over-excitation and over-inhibition. The authors proposed that these abnormal and unpredictable states of arousal interfered with the child’s capacity to maintain perceptual constancy as they varied the child’s awareness or experience of the same stimulus. Carl Delacato (1974) described possible sensory problems in autism and classified each sensory channel as being: *hyper*-: the channel is too open, as a result too much stimulation gets in for the brain to handle, *hypo*-: the channel is not open enough, as a result too little of the stimulation gets in and the brain is deprived, and *'white noise'*: the channel creates its own stimulus because of its faulty operation and, as a result the message from the outside world is overcome by the noise within the system. Delacato further stated that each sensory channel could be affected differently, a child could be hypovisual, 'white noise' auditory, hypo- to tastes and smell and hypertactile. More recent authors report of accounts where the same person could experience sensory inputs from one and the same channel at different times from all three of these categories, because the intensity (the volume) of these channels often fluctuates (Bogdashina, 2003). Another approach to the understanding of the various symptoms seen in autism was offered by Waterhouse et al. (1996) who proposed that difficulties with cross-modal integration of sensory information lie at the heart of the sensory symptoms of autism. They suggested abnormalities in the mossy fibers of the hippocampus to be the potential cause for this. This abnormality would result in a failure to bind all incoming sensory information from the same event or context with the spatiotemporal information resulting from this event or context, resulting in impaired cross-modal integration or "canalesthesia" as the authors term it.

3.3.2. Recent theories

The theory of impairment in intersensory processing has found further support in a recent review by Bahrick and Todd (2012). Much in line with our own hypotheses, the authors evaluate intersensory processing disturbance as a potential basis for explaining fundamental impairments in autism, including social and communicative functioning, as well as stereotyped and repetitive behaviours. They propose four ways in which impairments or imprecision in the detection of intersensory redundancy in ASD might affect the perception of multimodal events and render these processes more effortful than in typical development. Their intersensory redundancy hypothesis

(Bahrick & Lickliter, 2000) proposes a framework for understanding how and under what conditions attention is allocated to different properties of stimulation (amodal versus modality-specific), how salience hierarchies are created, and how this would guide perceptual development. First, Bahrick & Todd (2012) suggest that even minor impairments in the detection of synchrony and other amodal properties in infancy and beyond would compromise selective attention to multimodal events. These would in turn seem more disjoint and consist of more loosely connected streams of unimodal stimulation (piecemeal processing). As a result, stimulation from simultaneous but unrelated events (e.g., a fan blade turning) may be more easily confused and mixed up with more focal events (e.g., voice of a person). Second, the authors propose that imprecise synchrony detection may lead to impaired "unitization", which would result in reduced coherence and integration across modalities, as well as in the experience of a greater overall amount of perceived stimulation and complexity. Third, according to the authors, impairments in the detection of intersensory redundancy may lead to an alteration in the typical salience hierarchy, in which amodal information is detected prior to modality specific information. Finally, impaired detection of intersensory redundancy would also lead to enhanced unimodal visual and/or auditory processing.

Over the past decades, a group of cognitive theories of ASD emerged and attempted each in its own way to explain the origins of the various atypical behaviours observed in the developmental disorder. Aspects proposed by Bahrick and Todd (2012) find close ties in some of these prominent cognitive theories. While elaborating on aspects of compromised selective attention, the authors also refer to piecemeal processing and allude to the Weak Central Coherence (WCC) theory (Happé, 2005;

Happé & Frith, 2006). This theory proposes that individuals with ASD have a tendency to focus on details and have difficulty integrating "local" or specific features into a whole, and that they therefore have weak central coherence. In their second point, Bahrick and Todd (2012) refer to impairments in unitization, which brings back to mind the temporal binding hypothesis (Brock, Brown, Boucher, & Rippon, 2002). According to this theory, the local bias in ASD is related to a failure to integrate information from different specialized networks in the brain. The last two points by Bahrick and Todd (2012) are obviously in line with models of enhanced perceptual functioning (Mottron & Burack, 2001, 2006), which also suggests that individuals with ASD have a tendency to process sensory information at a local level. Altered salience hierarchies would then enhance attention to modality specific detail and promote processing of local over global information (Bahrick & Todd, 2012).

Beyond the specific theories alluded to here, the literature evidently offers many more, which all attempt to add puzzle pieces to the bigger picture of ASD, and with merit. However, currently the field of autism research is quite heavily loaded with many different theoretical approaches, which try to understand and fit most behavioural aspects of the condition within one framework. Like Bahrick and Todd (2012), used here as an example to demonstrate the point, the preponderance of theories have aspects to account for everything from causes to development and consequences of alterations in behaviour. In the end however, the intention of the present research was not to fit our results within the framework of one or the other of these theories or even to distinguish between these. As was shown here, there is tremendous overlap between concepts to understand the very same behavioural observations. Rather, our goal was to increase our understanding of the clinical presentation of autism and of how individuals with ASD process sensory information. After reviewing the literature on sensory symptoms and theories, we now briefly present the current evidence derived from the empirical testing of unisensory and multisensory processing in ASD.

3.4. Unisensory processing in ASD

While it is important to study the interplay of the senses, in order to get a better picture of how these senses are integrated to form a unified percept, it remains as crucial to understand what happens in each sense in isolation. If we find anomalies in one sense in isolation, this may obviously impact our understanding of how the senses are merged together. For this reason, findings on unisensory processing in the visual and tactile modalities are briefly reviewed hereafter.

3.4.1. Visual processing

Despite a massive body of literature on visual processing in ASD, no single underlying theory has emerged which could account for all the visual anomalies observed (Kenet, 2011). Research conducted to date on visual processing in ASD revealed anomalies at different levels of processing. Alterations have been found both in low-level visual processing (e.g., Bertone, Mottron, Jelenic, & Faubert, 2005; Milne, Swettenham, Hansen, Campbell, Jeffries, & Plaisted, 2002) as well as on high-level cognitive tasks (e.g., Shah & Frith, 1993), generally reflecting superior performances on tasks requiring local or detailed processing of visuo-spatial information while finding a decreased ability for the processing of more complex types of information requiring an integrative, dynamic or global analysis (e.g., Mottron & Burack, 2001; 2006; Dakin & Frith, 2005; Behrmann, Thomas, & Humphreys, 2006; Happé & Frith, 2006; Simmons, Robertson, McKay, Toal, McAleer, & Pollick, 2009). For instance, individuals with autism show an enhanced performance on the block design test (Shah & Frith, 1993), in reproducing impossible figures (Mottron, Belleville, & Menard, 1999), in identifying a simple shape embedded in a more complex shape (Jolliffe & Baron-Cohen, 1997; Shah & Frith, 1983) and in discriminating elementary visual information, within a visual search paradigm (O'Riordan & Plaisted, 2001).

3.4.2. Tactile processing

Although tactile sensitivity is commonly reported in ASD, it has received far less attention in the neuroscience literature than visual sensitivity (Wiggins, Robins, Bakeman, & Adamson, 2009). We review the few existing studies with regards to tactile perception in this section. However, these studies have examined the integration of vibro-tactile stimulation only and not evaluated the active use of touch, as we did in our study. To date, only few studies have employed rigorous psychophysical approaches to study tactile perception in autism, yielding mixed results so far. No differences have been found between autistic and typically developing children in the ability to discriminate the roughness of different grades of sandpaper or to detect synthetic fibers pressed on the skin of their arms (O'Riordan & Passetti, 2006). In contrast, Blakemore et al. (2006) demonstrated tactile hypersensitivity at the fingertip with superior detection of high-frequency (200 Hz), although not low-frequency (30 Hz), skin vibrations in adults with Asperger’s syndrome. Finally, Cascio et al. (2008) found similar thresholds for detecting light touch and innocuous sensations of warmth and cool on the palm and forearm of autistic adults compared to controls, along with an increased sensitivity to vibration on the forearm and increased sensitivity to thermal pain at both sites in the autism group. These findings suggest normal tactile perception along with certain areas of enhanced perception in autism (Cascio et al., 2008) similar to emerging findings in auditory and visual perception (Bertone et al., 2005; Mottron & Burack, 2001; Mottron, Peretz, & Menard, 2000).

3.5. Multisensory Processing in ASD

Finally, in the autism literature akin to perception research, we start to observe a similar shift of focus away from the study of the senses in isolation towards an understanding of the intertwining of the senses. Findings on multisensory integration in autism are slowly beginning to emerge, with only very few studies investigating the developmental course of these processes. We hereafter briefly examine evidence of multisensory skills and impairments in individuals with ASD, and look at the matter more extensively in the next chapter. The majority of research in the domain has been behavioural and has largely focused on the processing of multisensory audiovisual social stimuli related to communication, such as speech sounds (Brandwein et al., 2012). A distinction is made again between higher-order multisensory integration, being related to the use of socially relevant stimuli and the use of some type of language versus low-level integration, which does not employ socially relevant stimuli.

3.5.1. Higher-Order Multisensory Integration

Most studies indicate that the ability to integrate audiovisual speech is impaired in individuals with ASD. For example, investigation of the McGurk effect has shown that children and adolescents with autism report fewer fusions than typical children, reflecting that they are less likely to take the non-matching, visual syllable into account during speech perception (de Gelder, Vroomen, & van der Heide, 1991). This finding is consistent with later reports indicating deficits in autistic children in audiovisual speech integration tasks (Bebko, Weiss, Demark, & Gomez, 2006; Mongillo, Irwin, Whalen, Klaiman, Carter, & Schultz, 2008; Smith & Bennetto, 2007).

3.5.2. Low-Level Multisensory Integration

Fewer studies have focused on audiovisual integration for non-social stimuli and these have yielded mixed results so far. A study looking at the illusory flash effect found no differences in adults with autism as shown by the fact that for both groups the number of sounds presented significantly affected the number of flashes perceived (van der Smagt, van Engeland, & Kemner, 2007). However, others found difficulties in autistic children to form cross-modal associations between sound beeps and light flashes as reflected by smaller auditory evoked responses (Martineau, Roux, Adrien, Garreau, Barthelemy, & Lelord, 1992). These findings are corroborated by a case study (Bonneh et al., 2008) of A.M., a 13-year-old boy with autism, presenting with complaints of severe impairment in multisensory perception. In a series of psychophysical experiments, the authors investigated cross-modal interference at different levels of processing and found that abnormal processing of multimodal stimuli occurred without any apparent attentional load and with highly salient stimuli, thus providing the first empirical evidence for monochannel perception in autism. Given how little empirical work has been done in this area, there is certainly need for continued exploration using rigorous psychophysical controlled studies. Finally, to our knowledge, nobody looked at visual-tactile cross-modal integration in autism.

3.5.3. Development of Multisensory Processing Skills in ASD

Considering the role that multisensory processing can play in the overall adaptation of a human being and especially in a child in development, such as being a unifying factor that helps merge senses, we have to consider possible developmental consequences, if this process was to be compromised early on. The literature on the development of multisensory processing in ASD is extremely scarce. Two very recent studies looked at the developmental course of audio-visual integration, and found that autistic children either "caught up" with their typically developing peers (Taylor, Isaac, & Milne, 2010) or that they were fundamentally different in terms of their abilities and not just delayed (Brandwein et al., 2012). Given the little evidence on the matter, we were especially interested to study the developmental trajectory of MSI in ASD. We therefore chose a developmental sample for our first study, whereas we opted for an adult sample for our second study, precisely to avoid those same effects of maturation on the measure of attentional processing.

3.6. Neuroanatomy of ASD

A large amount of evidence attests to differences in neuroanatomy between autistic and non-autistic individuals. While these differences are not always consistent, with many potential contributors and explanations, we focus here on the most replicated findings, especially as they relate to brain regions involved in multisensory and attentional processing. However, it is important to keep in mind that many well-described behaviours in ASD do not have a clearly understood anatomical basis. An earlier predominating "modular" approach in autism research, where specific brain regions were measured as potentially being relevant to ASD features turned out to be only mildly fruitful (Herbert, 2011). More recently, unexpected findings have revealed increased brain size and widespread alterations in functional connectivity, challenging a modular approach to brain-behavior correlation (Herbert & Anderson, 2008).

Notwithstanding the approach to the understanding of these relationships, the literature shows evidence of the involvement of the limbic system, corpus callosum, basal ganglia, thalamus, cerebral cortex, white matter, cerebellum, brainstem, and ventricles (Herbert, 2011). Most researchers have found the corpus callosum to be reduced in size (Rice et al., 2005). Others combined functional and anatomical measures of connectivity, and found corpus callosum size reduction that correlated with a lower degree of integration of information (Just, Cherkassky, Keller, Kana, & Minshew, 2007). Because of the thalamus' central role as a relay station in brain information processing, it is of great interest in autism research (Herbert, 2011). Volumetric findings showed reduced thalamic volume relative to total brain volume (Tsatsanis, Rourke, Klin, Volkmar, Cicchetti, & Schultz, 2003) and decreased concentration in gray matter was found using voxel-based morphometry (Waiter, Williams, Murray, Gilchrist, Perrett, & Whiten, 2005). Growth trajectories for cerebral gray and white matter were compared in a large cross-sectional sample of autistic and typically developing children from 2-16 years old (Courchesne et al., 2001). While cerebral cortical gray matter was 12% greater in 2-3 year-old autistic participants, compared to TD children, by 6-9 years, this trend was inversed with an increase of

12% volume in controls versus a decrease of 2% in autistic children. Similar differences were also found in cerebral white matter, where autistic subjects started out with 18% more volume in early childhood, compared to controls, however showed only a 10% increase of volume in adolescence, as compared to early childhood. On the contrary, in controls a 59% increase was found in adolescence.

Following a growing body of literature implicating the cerebellum in attention functions, it was studied extensively in ASD and thereafter found to be the most consistent site of neuroanatomical abnormality (Bailey et al., 1998; Courchesne, 1997). Finally, years of brain imaging research on the neural underpinnings of ASD suggest that autism is not a strictly localized brain disorder, but rather a disorder involving multiple functional neural networks (Muller, 2007; Rippon, Brock, Brown, & Boucher, 2007). Some reviews accumulating neuroanatomical and neurofunctional findings have proposed disordered brain connectivity to be the common pathway to the ASD phenotype (e.g., Courchesne, Redcay, Morgan, & Kennedy, 2005; Schipul, Keller, & Just, 2011). These theories generally hypothesize that the short- and long-distance connections between cortical regions are compromised in autism, resulting in impaired integration of information at neural, cognitive, and social levels (Just et al., 2004; Wass, 2011). This has been supported by findings from functional connectivity MRI, which indicate abnormal communication between functional cortical networks and regions in autism (Muller, Shih, Keehn, Deyoe, Leyden, & Shukla, 2011). Anatomical evidence for diminished long-distance connectivity in autism includes findings of reduced integrity of the callosal fibers connecting sensory cortices and prefrontal areas (Barnea-Goraly, Kwon, Menon, Eliez, Lotspeich, & Reiss, 2004), of atypical developmental trajectories for cerebral white matter volume as previously mentioned (Courchesne et al., 2001), and from postmortem studies showing abnormal microcircuitry of minicolumns (Casanova, Buxhoeveden, Switala, Roy, 2002; Buxhoeveden, Semendeferi, Buckwalter, Schenker, Switzer, & Courchesne, 2006).

Chapter 4. Article 1

The Development of Multisensory Integration in Autism Spectrum Disorders: Psychophysical Measures Reveal Alterations in Visuo-Tactile Processing

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Development and Psychopathology, submitted.

4.1. Abstract

The simultaneous integration of multiple senses such as touch and vision is crucial in everyday life as it allows for the creation of a unified percept. Current theories of autism spectrum disorder (ASD) propose that alterations in basic sensory processing might underlie atypical sensory behaviours in ASD. Empirical testing for this hypothesis is starting to emerge predominantly in the study of audiovisual integration. No evidence exists with regards to the active use of visuo-tactile information in ASD. We conceived a cross-modal size discrimination task to assess the integrity and developmental course of visuo-tactile information in children with ASD (*N* = 21, aged 6-18 years), compared to age- and PIQ-matched typically developing (TD) children. In a simultaneous two-alternative forced-choice task, participants were asked to make a judgement on the size of two stimuli, based on unisensory (visual or tactile) or multisensory (visuo-tactile) inputs. Difference thresholds evaluated the smallest difference at which participants were capable to discriminate size. Children with ASD showed diminished performance and no maturational effects in both unisensory and multisensory conditions, compared to TD participants. The present study therefore extends previous results of alterations in multisensory processing in ASD to the visuo-tactile domain.

Keywords: autism spectrum disorders; size discrimination; multisensory processing; visuo-tactile processing; development

4.2. Introduction

“Reality to an autistic person is a confusing interacting mass of events, people, places, sounds and sights. There seem to be no clear boundaries, order or meaning to anything. A large part of my life is spent just trying to work out the pattern behind everything.” (Joliffe, 1992, p. 16). Therese Joliffe, an autistic researcher, succinctly summarizes the everyday chaos generated by autistic sensory problems. Her account is only one example amongst many anecdotal reports relating the wide range of sensory processing atypicalities observed in individuals with an autism spectrum disorder (ASD) (e.g., Cesaroni & Garber, 1991; Grandin, 1992; Williams, 1994). ASD are defined by atypical communication and social interaction, in the presence of repetitive and stereotyped behaviours (APA, 2000). Though not part of the current *DSM-IV-TR* (2000) 4ed., text rev. criteria, unusual sensory symptoms have been observed since its earliest descriptions and have received renewed interest in recent years (e.g., Asperger, 1944; Ben-Sasson et al, 2009; Bergman & Escalona, 1949; DeMeyer, 1976; Hermelin & O'Connor, 1970; Kanner, 1943; Kern et al., 2006; Leekam et al., 2007; O'Neill & Jones, 1997; Wing, 1969). Sensory-perceptual anomalies are observed in 69-95% of individuals (Baker et al., 2008; Baranek et al., 2006; Tomchek & Dunn, 2007), presenting one of the most common features associated with ASD. They have been found to manifest themselves very early in development, which makes them one of the most diagnostically relevant features of ASD at an early age (O'Neill & Jones, 1997). Prospective changes in the *DSM-5* reflect this shift in our understanding of the condition and the importance of sensory symptoms in the characterization of ASD by including sensory reactions as a new and separate item within the criterion of repetitive behaviours, restricted interests and sensory issues.

Despite the prevalence in the literature of anecdotal reports, which are still the prevailing accounts on sensory sensitivities and anomalies, objective studies exploring the origins and trying to explain these behaviours are still relatively scarce. Much attention has been given to the study of the senses in isolation. Altered visually-related perceptual information processing has been established in ASD through a large number of findings (e.g., Dakin & Frith, 2005; Simmons et al., 2009; for reviews), making the visual system likely the most studied sensory system in ASD. More recently, study of the auditory system in ASD has also benefitted from increased interest in the research community, whereas other sensory systems have been less explored, as for instance the tactile system. Finally, only few studies have looked at the integration of multiple sensory systems in ASD (Marco, Hinkley, Hill, & Nagarajan, 2011, for a review). However, the world being a sensory place, our everyday life consists of the interaction between different senses, and we are constantly faced with the task of filtering out redundant information or integrating multiple senses at the same time. Hence, when studying individuals with unusual sensory symptoms, not withstanding the importance of examining isolated sensory systems, it appears crucial to also study the interplay of the senses, creating a coherent percept (Iarocci & McDonald, 2006). Autobiographical accounts like the one by Therese Joliffe suggest possible anomalies at the level of integration of information from multiple sensory modalities. Over recent years the hypothesis that basic sensory processing differences may be underlying atypical sensory behaviours in ASD has emerged and is gaining momentum. Empirical testing of this idea is slowly starting to surface, with studies evaluating the integrity of multisensory integration (MSI) in ASD yielding mixed results so far.

Of the few existing studies, the majority have focused on the integration of visual and auditory input. Inconsistent results are in part due to variability in task complexity and type of stimuli. A large number of studies indicate impairment in the integration of audio-visual speech in ASD (de Gelder et al., 1991; Iarocci et al., 2010; Irwin et al., 2011; Magnee, de Gelder, van Engeland, & Kemner, 2008; Mongillo et al., 2008; Smith & Bennetto, 2007; Taylor, et al., 2010; Williams et al., 2004), whereas others have shown mixed results when using stimuli that are unrelated to communication (Foss-Feig et al., 2010; Kwakye et al., 2011; Mongillo et al., 2008; van der Smagt, van Engeland, & Kemner, 2007), finding either impairments or intact integration. The current evidence therefore shows intact MSI, as well as impairments in multisensory processing in ASD. However, the basis for these impairments in multisensory processing is still unclear (Bahrick & Todd, 2012). Some studies have found deficits in MSI in ASD, but did not measure the unisensory conditions, making it difficult to draw conclusions as to whether the impaired multisensory processing could be due to sensory processing in isolation (Bahrick & Todd, 2012). With regards to other modalities, a recent study examined the integrity of auditory-somatosensory integration in children with ASD, using electrophysiology, and found overall less extensive MSI in ASD (Russo et al., 2010). Further, Cascio et al. (2012) found delayed susceptibility to the rubber hand illusion in children with ASD, and proposed this to be a result of atypical multisensory temporal integration of visuo-proprioceptive information.

To date, no study has evaluated the processing of multisensory visuo-tactile information, requiring participants to actively use their sense of touch. Given that most objects are multimodal and object properties (e.g., size and shape) are experienced through multiple sense modalities, it appears important to evaluate how children and adolescents with ASD are able to process these properties across senses. For example when judging an object's size both the visual and the haptic modalities can provide information (Helbig & Ernst, 2007), and these multiple sensory inputs are generally integrated into a unified percept. Cross-modal sensory integration of form information therefore is a crucial part of perception with high adaptive value, with size being a fundamental aspect that can be studied by psychophysical methods. In the present study, we used a cross-modal size discrimination task in order to investigate unisensory visual and tactile, as well as multisensory visuo-tactile processing in children and adolescents with ASD and typical development (TD).

Research has shown that sensory systems mature over time and that development influences the perception of multisensory integration (e.g., Brandwein et al., 2011; Gori, Del Viva, Sandini, & Burr, 2008; Ross et al., 2011). As a consequence, even small differences in multisensory processing skills could amplify across development and result in substantial differences in attention to social events as well as producing cognitive differences in later development (Bahrick & Todd, 2012). Few studies have approached the evaluation of multisensory processing in ASD from a developmental perspective, and all of these have examined the integration of visual and auditory input. Findings so far show that children with ASD either "catch up" to their matched controls in teenage years, in studies using a speech-in-noise paradigm (Foxe et al., 2009; Taylor et al., 2010) or on the contrary, that they integrate simple, non-social stimuli fundamentally differently (Brandwein et al., 2012). In order to further our understanding of these processes in the visual and tactile systems in ASD, we also assessed the developmental trajectory of visuo-tactile processing by studying children and adolescents from 6 to 18 years old.

4.3. Method

Participants

Twenty-one individuals with typical development (TD) and 21 individuals with ASD between the ages of 6 and 18 years participated in this study (see Table 1). ASD individuals were recruited from a specialized school for children with ASD, where a formal diagnosis of ASD is an admission criterion. A diagnosis of ASD had been made by experienced clinicians on the basis of diagnostic criteria outlined in the *DSM-IV* (4th ed.; *DSM-IV*; American Psychiatric Association, 1994), using one or a combination of the following: the algorithm of the Autism Diagnostic Observation Schedules (ADOS) (Lord et al., 1989; Lord et al., 2000), the Autism Diagnostic Interview (ADI) (Le Couteur et al., 1989; Lord, Rutter, & Le Couteur, 1994) and/or a DSM-based clinical interview. Of the 21 ASD participants, 15 had a diagnosis of autistic disorder, and 6 of pervasive developmental disorder-not otherwise specified (PDD-NOS). TD participants were recruited from the community, and all had a typical development. Both groups were screened for any (additional) past or current history of psychiatric, neurological, or medical disorder and visual impairment, and were administered the Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999). Participants were group matched on the basis of performance IQ (PIQ), gender and age. An analysis of variance (ANOVA) revealed that there were no significant differences between the TD and ASD groups in PIQ (*F* (1, 41) = 3.198, *P* = 0.081) or in Age (*F* (1, 41) = 0.093, *P* = 0.762). Exclusionary criteria for both groups included a PIQ below 80 and other developmental *DSM-IV* (1994) 4th ed. Axis 1 diagnoses, except hyperactivity for the ASD group given the frequent comorbidity of attention abnormalities in ASD, as well as uncorrected vision problems. Two ASD participants exhibited symptoms of hyperactivity, however did not have a formal diagnosis of ADHD. All participants had normal or corrected-to-normal vision (20/20 Snellen acuity for both eyes) and binocular vision, as evaluated by the Randot Stereotest (Stereo Optical Co.). Informed written consent was obtained from all participants, and the research was prospectively reviewed and approved by the University of Montreal's Ethics Committee.

[INSERT TABLE 1 APPROXIMATLEY HERE]

Materials

Cross-modal Size Discrimination Task. A transportable task in a carrying case, much like a neuropsychological assessment battery, was custom-built and allowed for flexible testing in a school environment (Figure 1). The interior of the case is composed of a hinged aluminum set-up (45 x 20 cm) with a demountable cover on top, a removable partition in the middle and an aperture with a black curtain in front, which unfolds on one side of the case. The set-up is open at the back to allow for placement of stimuli from this side, which comprises six rows with eight grooves each containing coin-like stimuli that are organized in a pre-arranged order for experimentation. At the base of the set-up, two housings indicate stimuli location.

[INSERT FIGURE 1 APPROXIMATLEY HERE]

Stimuli. 20 pairs of stimuli made of bronze, for a total of 40 stimuli, were custom-built and manufactured individually, at a precision of 2,5 μm, by means of a specially designed program for each one of them using a computer numerical controlled (CNC) machine in a CNC turning center. Stimuli have a coin-like appearance and differ in diameter. Their surface contains no texture and all stimuli have identical thickness (3 mm). Stimulus differences vary by 25% following a logarithmic scale and range from 19% to 0, 3%. The geometrical mean of any pair of stimuli is 25 mm.

Design and Procedure

Testing environment. ASD participants were evaluated in their familiar school environment, at the Canadian Institute for Neuro-Integrative Development (Giant Steps School), and TD participants in an identical setting at the laboratory. ASD participants were seen for two one-hour evaluations at two different time points within an interval of two to three weeks in a specific testing room at their school. During the first evaluation, subjects underwent a brief visual exam and were administered the WASI, in order to establish eligibility for study participation and become familiarized with the experimenter. During the second evaluation, participants passed the cross-modal size discrimination task. TD participants were seen in one single two-hour visit to the laboratory, in order to avoid additional travel for participants and their parents.

Conditions. In a simultaneous two-alternative forced-choice task, an adaptive staircase method (Levitt, 1971) was employed to measure difference thresholds for three different modalities. Participants were presented two stimuli simultaneously and asked to judge which was the bigger on the basis of *visual*, *tactile* or *cross-modal visuo-tactile* information (Figure 2). (A) In the *visual* condition, the cover of the set-up was taken off, in order for participants to see visually presented stimuli without touching them. One pair of stimuli at a time was presented to participants. (B) In the *tactile* condition, participants reached with both hands in the aperture behind the black curtain, in order to feel the stimuli without seeing them. Participants were asked to decide by touch of fingertip (thumb and index finger) only which of the two presented stimuli was bigger. (C) In the *cross-modal visuo-tactile* condition, participants examined one stimulus visually, while simultaneously exploring the second stimulus tactually without seeing it. For this condition, the tactually felt stimulus was always presented on the side of the participant's dominant hand, and the visual stimulus on the opposite side. The side where the tactually perceived stimulus was presented was covered so that participants only felt the stimulus without seeing it.

[INSERT FIGURE 2 APPROXIMATLEY HERE]

Viewing distance was maintained constant across conditions at 40 cm (visual angle: 3, 20° x 2, 86°). A pair of stimuli was always presented for 2 s before participants were asked to judge which one was the bigger (guessing if unsure) by sign of hand indicating left or right. Positioning of the stimuli took ~ 2 s. Stimuli were presented at 2 cm distance from each other. Prior to experimentation, a practice trial of each condition was administered to ensure proper familiarization with the task. The experimental conditions (visual, tactile and cross-modal) were presented 2 times each (for a total of six trials). Order of administration of conditions was randomized for three trials at a time and every comparison participant was presented with the same order of administration of conditions as their matched ASD participant.

Measures

Adaptive staircase. A two-down-one-up adaptive staircase method was used in order to obtain 70.7 % difference thresholds (Levitt, 1971). In our experiment, the step size was decreased in the course of each experimental trial as recommended by numerous authors (Chung, 1954; Levitt, 1971; Robbins & Monro, 1951; Shelton & Scarrow, 1984). The employed adaptive staircase method commenced with a step size of 4 until two reversals were reached, followed by a step size of 2 for another two reversals, whereupon it finished with a step size of 1 for the last six inversions. This procedure allowed for participants' familiarization with the task, in addition to prior practice trials, and made sure that the task was not too difficult in the beginning, hence avoiding frustration of participants. For all three conditions (visual, tactile and cross-modal), the staircase began with the same stimulus difference. During administration, only reversals were recorded permitting to retrace subjects' answers following completion of experimentation. In total, ten inversions were recorded for each condition within a range of 20 stimulus pairs, and the mean was obtained from the last six inversions at a step size of 1. The difference thresholds corresponding to these inversions were then converted into a geometrical mean, which corresponds to participants' difference thresholds for each trial. Participants' performance was calculated by averaging results obtained on the two trials administered for each condition.

4.4. Results

Cross-modal Size Discrimination in ASD

For statistical analyses, a mixed-factorial ANOVA was used to look at group effects, and multiple regression models in combination with slope analysis were used to examine maturational effects. Raw scores were converted to log values for analyses.

A 2 x 3 split-plot ANOVA (group (between) x modality (within)) revealed a significant main effect of group (F [1, 40] = 26.54, $p < .001$, $\eta 2 = .40$), demonstrating that whatever the condition, ASD participants were generally less able to discriminate the size of the two coins in comparison to matched TD participants. A significant main effect of modality (F [2, 80] = 69.99, $p < .001$, $\eta^2 = .66$) was found and a priori contrast measures showed that both groups performed significantly better (i.e., showed lower difference thresholds) in the visual ($M = 0.013$, $SD = 0.006$) than in the tactile ($M = 0.034$, $SD = 0.015$), t (39) = 10.50, $p < .001$, $d = 1.84$ and the cross-modal conditions ($M = 0.033$, $SD = 0.022$), t (39) = 6.67, $p < .001$, $d = 1.24$. No significant group x modality interaction was found, $F(2, 80) = 0.23$, $p > .05$, $\eta 2 = .01$.

In order to assess developmental changes in MSI in the ASD and TD groups, multiple regression analyses were conducted, where difference thresholds for both groups were regressed on chronological age for each condition separately. Figure 3 shows difference thresholds for ASD and TD individuals for visual, tactile and visuo-tactile conditions as a function of chronological age. The two predictor variables, group and age were not significantly correlated amongst each other ($r = .048$, $p > .05$). Group was significantly correlated with all three outcome variables (visual: $r = .578$, $p < .001$; tactile: $r = .415$, $p < .05$; visuo-tactile: $r = .503$, $p = .001$), and age was significantly correlated with the visual condition ($r = .344$, $p < .05$), however not with tactile ($r = .194$, $p > .05$) and visuo-tactile ($r = .129$, $p > .05$) conditions. For the visual condition, an ANOVA comparing the slopes of the regressions for both groups was found to be statistically significant, revealing a significant group x age interaction, $F(2, 38) = 28.269$, $p < .001$. This indicates that visual size discrimination abilities develop differently with age for the TD and the ASD groups. When examining the development of these abilities in both groups separately, the ANOVA was found to be statistically significantly in the TD group ($R^2 = .394$, $F(1, 20) = 12.371$, $p < .05$), showing that in TD participants, performance in visual size discrimination improved as a function of age, whereas this was not the case in the ASD group ($R^2 = .034$, $F(1, 20) = 0.665$, $p > .05$). Finally, the ANOVA comparing regressions for the visuo-tactile condition was equally statistically significant, showing a group x age interaction as reflected by the slope parameter being significantly different from zero at the 0.5% level, $F(2, 38) = 7.447$, $p < .05$. This shows that visuo-tactile size discrimination abilities also develop differently with age for the TD and the ASD groups. No significant differences in the slope parameter were found for the tactile condition, $F(2, 38) = 0.444$, $p > .05$, indicating no effect of age in this condition.

[INSERT FIGURE 3 APPROXIMATLEY HERE]

4.5. Discussion

The present study used a cross-modal size discrimination task to assess visual, tactile and multisensory visuo-tactile abilities across typically developing individuals and individuals with ASD. To our knowledge, this study constitutes the first assessment of visuo-tactile processing abilities in ASD, including an account of the developmental course of these abilities. TD and ASD children and adolescents performed better when asked to discriminate the size of two coins in the visual than the tactile and visuo-tactile conditions. This is reflected by decreased difference thresholds found in both groups in the visual condition. For both groups, we did not find a significant difference between the tactile and cross-modal conditions, indicating that the unisensory tactile condition was more difficult to complete than the unisensory visual condition. We obtained two main findings. First, ASD individuals were less able than TD individuals to discriminate the size of two coins in both unisensory and multisensory conditions, as measured by increased difference thresholds on all three conditions for ASD participants. Second, we found no maturational effects of unisensory or multisensory abilities in ASD participants. Whereas we found that TD participants' visual abilities matured with age, this was not the case for the ASD group. Most importantly, the ASD group did not benefit from any type of facilitation in the CM condition, as shown by significant differences between the slopes of the two groups in this condition.

Multisensory processing in ASD. Previous studies have found evidence for intact as well as impaired integration of multisensory information in ASD, with findings often depending on task complexity, as well as the use of low level or higher order stimuli, including stimuli related to speech and communication. Given that there is still a scarcity of results on MSI across the visual and tactile systems, we can only draw tentative comparisons with previous findings in other modalities. One other study has looked at the integration of vision and touch in a higher level task, using the rubber hand illusion paradigm, and also found anomalies in the integration of vision and touch, as reflected by a delay in susceptibility to the illusion (Cascio et al., 2012). The authors have drawn parallels from other modalities, suggesting the observed delay to be consistent with previous findings of their group, demonstrating an extended temporal window of audiovisual binding in ASD (Foss-Feig et al., 2010; Kwakye et al., 2011). Since many factors can influence the integration of vision and touch in a higher order task such as the rubber hand illusion, it may not be entirely clear if the impairments observed are due to the complex nature of the task, involving aspects of social interaction, or to multisensory processing deficits per se.

Low-level studies measuring MSI in ASD in the audiovisual domain have yielded mixed results so far. For instance, intact perception of the illusory flash effect was found in adults with ASD (van der Smagt, van Engeland, & Kemner, 2007). However, it was shown that disparity between the auditory and visual stimulus onset times can impact the effect of the illusion in children with ASD (Foss-Feig et al., 2010; Kwakye et al., 2011). Most recently, Brandwein et al. (2012) showed an absence of multisensory facilitation using a simple audiovisual reaction time task. Finally, our findings of alterations in multisensory processing across visual and tactile domains are also consistent with results in the auditory-somatosensory domain that showed overall less extensive MSI in ASD (Russo et al., 2010).

Amongst the studies looking at higher-order processes involving aspects of communication, some have shown unique multisensory processing deficits beyond any unisensory deficits (e.g., Smith & Bennetto, 2007). Using a speech in noise task, these authors found that individuals with ASD required larger signal to noise ratios (louder speech signals compared to background noise) than TD participants, which suggested less benefit from the visual stimulus and hence impaired integration. Once controlled for unisensory visual (lip reading) impairments, the deficits in audiovisual speech processing were maintained and thus attributed to unique multisensory deficits. However, the fact remains that there were unimodal sensory differences between ASD and TD groups. Therefore, one cannot exclude the hypothesis that the unimodal alterations impacted the development of efficient MSI mechanisms. Other studies have found that impairments in multisensory processing were accounted for by deficits in unisensory visual processing (e.g., Williams et al., 2004). This seemed to be the case in our study as well. Whereas we have found the ASD group to perform significantly less well on the multisensory task, they also performed significantly worse on both unisensory tasks compared to the TD participants. Although, for both groups, the tactile condition seemed to constitute the limiting factor, TD participants were able to benefit from the visual input on the multisensory condition. The integration in the TD group is shown by the fact that their performance seems to be a combined input of the two unisensory conditions. However, ASD participants' performance appeared to be limited by their lowest common denominator, the tactile condition, as reflected by their performance on both the tactile and multisensory conditions being almost identical.

Thus, while for the TD group vision impacted their ability to make the judgement across senses, the ASD group was unable to benefit from this facilitation. Our findings therefore corroborate previous findings that indicate a close connection between unisensory and multisensory abilities, with deficits in unisensory processing having clear effects on multisensory integration (Bahrick & Todd, 2012). Interestingly, Williams et al. (2004) showed that impairments in multisensory processing improved following training in the unisensory visual modality (lip reading), and hence demonstrated successful transfer of unimodal visual skills to facilitate multisensory processing in ASD. In our study, we observed that unisensory conditions alone were already challenging to complete for ASD participants. Although our task constitutes a low-level task in that we did not use any socially relevant stimuli, it remains to be considered that size discrimination involves a spatially distributed comparison. Given that participants were asked to simultaneously compare two coins, we were not measuring detection abilities, for which ASD individuals have often been found to show increased performance (e.g., O'Riordan & Plaisted, 2001; Shah & Frith, 1993). Rather, participants were required to use spatial characteristics to make a comparison between two inputs, therefore increasing the complexity level of the task. This may have influenced the decreased performance in unisensory conditions in the ASD group. The current literature offers a family of theories of ASD (e.g., Brock et al., 2002; Frith & Happé, 1994; Just, Cherkassky, Keller, & Minshew, 2004) in line with our findings. Notwithstanding the theoretical underpinnings, we want to emphasize the understanding of how basic MSI functions in ASD and how individuals with ASD make use of this information.

Development of multisensory processing in ASD. Given the many important roles of MSI in our everyday life, acting from glue that binds information across senses to being a buffer against learning inappropriate associations across the senses, we can imagine how impairment in these processes may alter developmental trajectories and how they may become more effortful (Bahrick & Todd, 2012). Previous studies across other sensory modalities have found that children with ASD would either "catch up" (Foxe et al., 2009; Taylor et al., 2010) or rather be fundamentally different (Brandwein et al., 2012) in their abilities to process multisensory information. Studies showing that ASD individuals "caught up" to their same age peers in teenage years looked at AV speech integration, whereas Brandwein et al. (2012), using simple AV stimuli, found ASD individuals not to be developmentally delayed or simply immature, but rather to be fundamentally different. Our study corroborates these most recent findings of a fundamental difference in MSI in children with ASD. We found no development over time in the multisensory condition, however a significant difference between the slopes of both groups in this condition.

Conclusions and future directions. Our study has shown that children with ASD process visuo-tactile stimuli differently than TD children. Many of the atypical perceptual experiences reported in individuals with ASD are believed to be due to an inability to properly filter or process simultaneous channels of visual, auditory, and tactile inputs (O'Neill, 1997). Due to the ecological validity of our task, it is possible to suggest implications of our findings in regards to the day-to-day life of an individual with ASD. Given that integration of visuo-tactile information in the everyday experience and interaction with objects is fundamental, below optimal integration of visuo-tactile information could mean that individuals with ASD benefit less from an overall reduction of information load. For example, these children may have to put more effort into processing the redundant visuo-tactile information inherent in objects in their environment. As proposed earlier, we have to consider the possible cascading effects of alterations in the unisensory as well as multisensory abilities on the global development of a child. It also remains to be seen if training in unisensory conditions of low-level tasks like ours could equally enhance performance on the multisensory condition, as has been shown by previous studies. If this was the case, there could be an argument to extend existing forms of therapies to include more sensory stimulation. Finally, given that this has been the first study to examine the active use of visuo-tactile abilities in ASD, there certainly is a need for future research to replicate and extend our findings, especially given that the tactile system in ASD has been far less studied to date.

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4.7. References

American Psychiatric Association (1994). *Diagnostic and statistical manual of mental disorders* (4th ed.). Washington, DC: American Psychiatric Association.

American Psychiatric Association (2000). *Diagnostic and statistical manual of mental disorders* (4th ed., text rev.). Washington, DC: American Psychiatric Association.

Asperger H. 1944. Die “Autistischen Psychopathen” im Kindesalter. *Archiv für Psychiatrie und Nervenkrankheiten, 117*, 76–136.

Bahrick, L. E. & Todd, J. T. (2012). Multisensory processing in autism spectrum disorders: Intersensory processing disturbance as a basis for atypical development. In B.E. Stein (Ed.), *The new handbook of multisensory processes* (pp. 657-674). Cambridge, MA: MIT Press.

Baker, A. E., Lane, A., Angley, M. T., & Young, R. L. (2008). The relationship between sensory processing patterns and behavioural responsiveness in autistic disorder: a pilot study. *Journal of Autism and Developmental Disorders, 38*(5), 867-875.

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

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

Bergman, P., & Escalona, S. K. (1949). Unusual sensitivities in very young children. *Psychoanalytic Study of the Child, 3*(4), 333-352.

Brandwein, A. B., Foxe, J. J., Butler, J. S., Russo, N. N., Altschuler, T. S., Gomes, H. & Molholm, S. (2012). The Development of Multisensory Integration in High-Functioning Autism: High-Density Electrical Mapping and Psychophysical Measures Reveal Impairments in the Processing of Audiovisual Inputs. *Cerebral Cortex*. 2012 May 24. [Epub ahead of print].

Brandwein, A. B., Foxe, J. J., Russo, N. N., Altschuler, T. S., Gomes, H. & Molholm, S. (2011). The development of audiovisual multisensory integration across childhood and early adolescence: a high-density electrical mapping study. *Cerebral Cortex 21*(5), 1042-1055.

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

Cascio, C. J., Foss-Feig, J. H., Burnette, C. P., Heacock, J. L., & Cosby, A. A. (2012). The rubber hand illusion in children with autism spectrum disorders: delayed influence of combined tactile and visual input on proprioception. *Autism*. 2012 Mar 7. [Epub ahead of print].

Cesaroni, L., & Garber, M. (1991). Exploring the experience of autism through firsthand accounts. *Journal of Autism and Developmental Disorders, 21*(3), 303-313.

Chung, K. (1954). On a stochastic approximation method. *Annals of Mathematical Statistics, 25*, 463-483.

Dakin, S., & Frith, U. (2005). Vagaries of visual perception in autism. *Neuron, 48*(3), 497-507.

de Gelder, B., Vroomen, J., & van der Heide, L. (1991). Face recognition and lip-reading in autism. *European Journal of Cognitive Psychology 3*, 69-86.

DeMeyer, M. K. (1976). Motor, perceptual-motor and intellectual disabilities of autistic children. In L. Wing (Ed.), *Early childhood autism* (pp. 169-193). Oxford, UK: Pergamon Press.

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

Foxe, J. J. & Molholm, S. (2009). Ten years at the Multisensory Forum: musings on the evolution of a field. *Brain Topography, 21*(3-4), 149-154.

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

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

Grandin, T. (1992). An inside view of autism. In Schopler & Mesibov (Eds.), *High-functioning individuals with autism* (pp. 105-126). New York: Plenum Press.

Helbig, H. B., & Ernst, M. O. (2007). Optimal integration of shape information from vision and touch. *Experimental Brain Research, 179*(4), 595-606.

Hermelin, B., & O'Connor, N. (1970). *Psychological experiments with autistic children*. Oxford, UK: Pergamon Press.

Iarocci, G., & McDonald, J. (2006). Sensory integration and the perceptual experience of persons with autism. *Journal of Autism and Developmental Disorders, 36*(1), 77-90.

Iarocci, G., Rombough, A., Yager, J., Weeks, D. J., & Chua, R. (2010). Visual influences on speech perception in children with autism. *Autism, 14*(4), 305-320.

Irwin, J. R., Tornatore, L. A., Brancazio, L., & Whalen, D. H. (2011). Can children with autism spectrum disorders "hear" a speaking face? *Child Development, 82*(5), 1397-1403.

Jolliffe, J., Lansdown, R., & Robinson, C. (1992). Autism: a personal account. Communication. *Journal of the National Autistic Society,* 12-19.

Just, M. A., Cherkassky, V. L., Keller, T. A. & Minshew, N. J. (2004). Cortical activation and synchronization during sentence comprehension in high-functioning autism: evidence of underconnectivity. *Brain, 127*(Pt 8), 1811-1821.

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

Kern, J. K., Trivedi, M. H., Garver, C. R., Grannemann, B. D., Andrews, A. A., Savla, J. S., Johnson, D. G., Mehta, J. A. & Schroeder, J. L. (2006). The pattern of sensory processing abnormalities in autism. *Autism 10*(5), 480-494.

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

Le Couteur, A., Rutter, M., Lord, C., Rios, P., Robertson, S., Holdgrafer, M. & McLennan, J. (1989). Autism diagnostic interview: a standardized investigator-based instrument. *Journal of Autism and Developmental Disorders, 19*(3), 363-387.

Leekam, S. R., Nieto, C., Libby, S. J., Wing, L., & Gould, J. (2007). Describing the sensory abnormalities of children and adults with autism. *Journal of Autism and Developmental Disorders, 37*(5), 894-910.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49*(2), 467-477.

Lord, C., Risi, S., Lambrecht, L., Cook, E. H., Jr., Leventhal, B. L., DiLavore, P. C., Pickles, A. & Rutter, M. (2000). The autism diagnostic observation schedule-generic: a standard measure of social and communication deficits associated with the spectrum of autism. *Journal of Autism and Developmental Disorders, 30*(3), 205-223.

Lord, C., Rutter, M., Goode, S., Heemsbergen, J., Jordan, H., Mawhood, L. & Schopler, E. (1989). Autism diagnostic observation schedule: a standardized observation of communicative and social behavior. *Journal of Autism and Developmental Disorders, 19*(2), 185-212.

Lord, C., Rutter, M., & Le Couteur, A. (1994). Autism Diagnostic Interview-Revised: a revised version of a diagnostic interview for caregivers of individuals with possible pervasive developmental disorders. *Journal of Autism and Developmental Disorders, 24*(5), 659-685.

Magnee, M. J., de Gelder, B., van Engeland, H. & Kemner, C. (2008). Audiovisual speech integration in pervasive developmental disorder: evidence from event-related potentials. *Journal of Child Psychology and Psychiatry, 49*(9), 995-1000.

Marco, E. J., Hinkley, L. B., Hill, S. S., & Nagarajan, S. S. (2011). Sensory processing in autism: a review of neurophysiologic findings. *Pediatric Research, 69*(5 Pt 2), 48R-54R.

Mongillo, E. A., Irwin, J. R., Whalen, D. H., Klaiman, C., Carter, A. S., & Schultz, R. T. (2008). Audiovisual Processing in Children with and without Autism Spectrum Disorders. *Journal of Autism and Developmental Disorders, 38*(7), 1349-1358.

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

O'Neill, M., & Jones, R. S. (1997). Sensory-perceptual abnormalities in autism: a case for more research? *Journal of Autism and Developmental Disorders, 27*(3), 283-293.

Robbins, H., & Monro, S. (1951). A stochastic approximation method. *Annals of Mathematical Statistics, 22*, 400-407.

Ross, L. A., Molholm, S., Blanco, D., Gomez-Ramirez, M., Saint-Amour, D. & Foxe, J. J. (2011). The development of multisensory speech perception continues into the late childhood years. *European Journal of Neuroscience, 33*(12), 2329-2337.

Russo, N., Foxe, J. J., Brandwein, A. B., Altschuler, T., Gomes, H., & Molholm, S. (2010). Multisensory processing in children with autism: high-density electrical mapping of auditory-somatosensory integration. *Autism Research, 3*(5), 253-267.

Shah, A. & Frith, U. (1993). Why do autistic individuals show superior performance on the block design task? *Journal of Child Psychology and Psychiatry, 34*(8), 1351-1364.

Shelton, B. R., & Scarrow, I. (1984). Two-alternative versus three-alternative procedures for threshold estimation. *Perception & Psychophysics, 35*(4), 385-392.

Simmons, D. R., Robertson, A. E., McKay, L. S., Toal, E., McAleer, P., & Pollick, F. E. (2009). Vision in autism spectrum disorders. *Vision Research, 49*(22), 2705-2739.

Smith, E. G., & Bennetto, L. (2007). Audiovisual speech integration and lipreading in autism. *Journal of Child Psychology and Psychiatry, 48*(8), 813-821.

Taylor, N., Isaac, C. & Milne, E. (2010). A comparison of the development of audiovisual integration in children with autism spectrum disorders and typically developing children. *Journal of Autism and Developmental Disorders, 40*(11), 1403-1411.

Tomchek, S. D., & Dunn, W. (2007). Sensory processing in children with and without autism: a comparative study using the short sensory profile. *American Journal of Occupational Therapy, 61*(2), 190-200.

van der Smagt, M. J., van Engeland, H., & Kemner, C. (2007). Brief Report: Can You See What is Not There? Low-level Auditory-visual Integration in Autism Spectrum Disorder. *Journal of Autism and Developmental Disorders, 37*(10), 2014-2019.

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

Williams, D. (1994). *Somebody somewhere*. London, UK: Doubleday.

Williams, J. H., Massaro, D. W., Peel, N. J., Bosseler, A., & Suddendorf, T. (2004). Visual-auditory integration during speech imitation in autism. *Research in Developmental Disabilities, 25*(6), 559-575.

Wing, L. (1969). The handicaps of autistic children--a comparative study. *Journal of Child Psychology and Psychiatry, 10*(1), 1-40.

4.8. Tables, Legends & Figures

Table 1.

Participant Characteristics for the Autism Spectrum Disorders (ASD) and Typically Developing (TD) Groups

	TD	*ASD*
Age	12.14 (3.44)	11.81 (3.66)
PIQ	108.33 (8.67)	102.19 (13.14)
N	21	21
No of males	17	17

Values within parenthesis represent SD.

Figure Captions

Figure 1. Illustration of the Cross-modal Size Discrimination Task.

Figure 2. Illustration of the different conditions in the Cross-modal size discrimination task: Visual (2a), Tactile (2b), Visuo-tactile (2c)

Figure 3. Individual difference thresholds for visual, tactile and visuo-tactile conditions for ASD and TD participants as a function of age. Lines represent linear regression.

Figure 1.

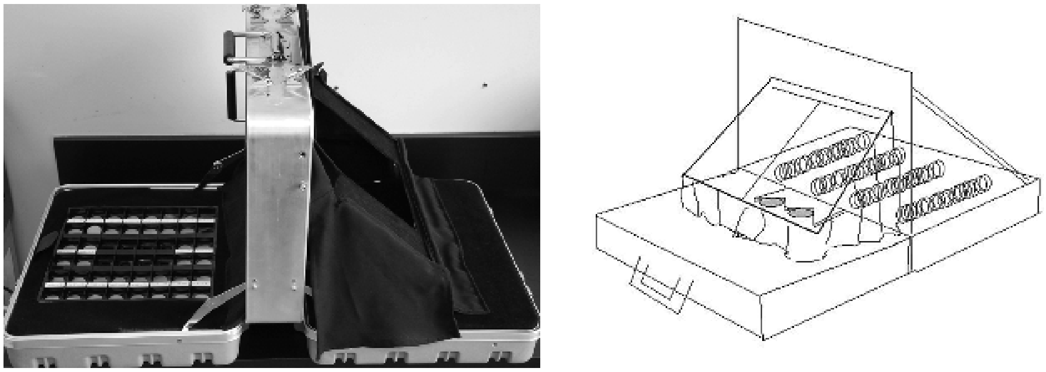


Figure 2.

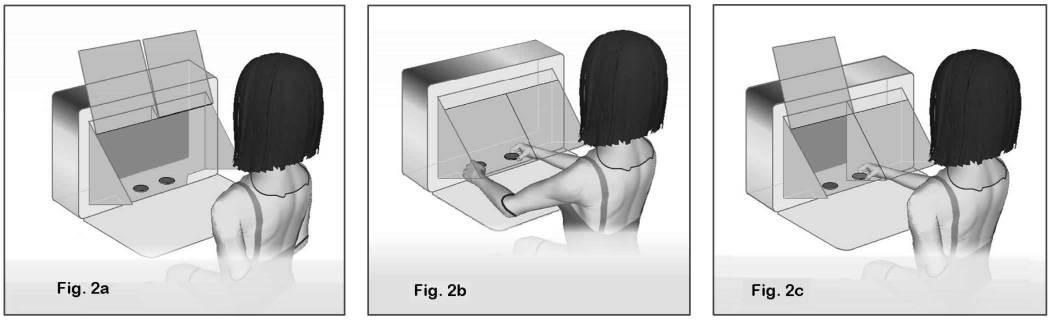
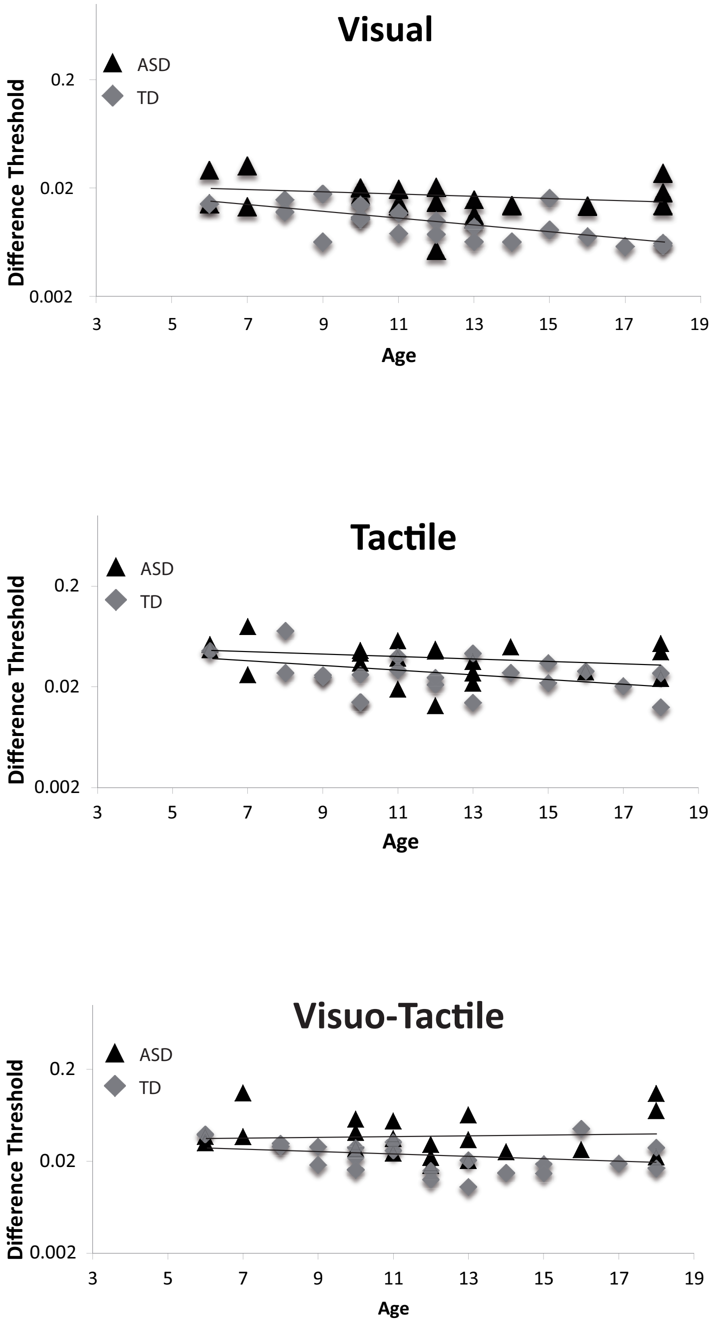


Fig. 2a

Fig. 2b

Fig. 2c

Figure 3.


Visual
▲ ASD
◆ TD
Difference Threshold
0.2
0.02
0.002
3
5
7
9
11
13
15
17
19
Age
Tactile
▲ ASD
◆ TD
Difference Threshold
0.2
0.02
0.002
3
5
7
9
11
13
15
17
19
Age
Visuo-Tactile
▲ ASD
◆ TD
Difference Threshold
0.2
0.02
0.002
3
5
7
9
11
13
15
17
19
Age

Chapter 5. Multiple Object Tracking

The second part of this thesis focuses on Multiple Object Tracking (MOT) and the capabilities thereof in autistic individuals. MOT is a perceptual-cognitive task that links attentional processing with aspects of visual and motion perception. Based on autobiographical accounts of unease in many natural and everyday tasks that require MOT-type capacities, we presumed that the capacity to track multiple objects would be different, and possibly diminished for this population. Given that the MOT task involves additional aspects of processing, compared to the Cross-modal size discrimination task, used in the previous study, we chose a sample of autistic adults for our second investigation, in order to avoid any confounding effects of maturation. This is in line with recent findings that found impairments in the development of biological motion processing in autistic children (Annaz et al., 2010). Prior to the presentation of our second study, we review the literature on attention functions in ASD, and present current models of MOT, followed by a brief section on processing of MOT-type information in the brain.

5.1. Attention in ASD

As Marco et al. (2011) point out the discussion of sensory processing in ASD would be incomplete without considering the role of attention on these cognitive processes. Blackburn, an autistic adult, suggests: "Sensory issues and attentional issues are most likely both real and both primary; in some case one may help cause the other. Both attentional and sensory problems may have developmental consequences that help to create the full autistic syndrome" (Blackburn, 1999, p. 7). Although not part of the current diagnostic criteria, much like sensory symptoms, difficulties in attention are very common and among the most thoroughly investigated cognitive deficits in ASD (Allen & Courchesne, 2001). Akin to alterations in sensory processing, differences in attentional functioning may be central to many social and cognitive deficits in autistic individuals, as efficient attending is essential to the development of all aspects of functioning (Bogdashina, 2003). At times, individuals with ASD seem to have poor attention skills and a tendency to attend to irrelevant details, while missing out on more relevant information in the environment. However, at others, the same individual may show the ability to intensely focus their attention on the task at hand (Travers, Klinger, & Klinger, 2011).

Attention is challenging to define. It is a relatively broad cognitive concept that includes a set of mechanisms that determine how particular sensory input, perceptual objects, trains of thought, or courses of action are selected for further processing from an array of concurrent possible stimuli, objects, thoughts and actions (Pashler, 1999). In order to function in his environment, an individual must be able to select certain sensory inputs for enhanced processing while either filtering out or suppressing others (Marco et al., 2011). This process can further be divided into operations of selective, sustained and spatial attention, amongst others. Major findings in these three areas in ASD are reported here.

5.1.1. Selective Attention

With regards to the widening and narrowing of attention, research has found evidence of both, an overly narrow, as well as an overly broad focus of attention (Travers, Klinger, & Klinger, 2011). An overly narrow focus has been reported and may contribute to the presence of savant skills (isolated exceptional ability in one domain), which are found in a small portion of individuals with ASD (Fein, Tinder & Waterhouse, 1979; Lovaas, Schreibman, Koegel & Rehm, 1971; Wainwright & Bryson, 1996). Early evidence for an overly narrow focus stems from the work of Lovaas and colleagues in the early 1970s, who demonstrated "stimulus overselectivity", wherein autistic children responded to a restricted range of environmental stimuli, suggesting that their attention was overly focused or "overselective" (Lovaas & Schreibman, 1971). This notion of overselectivity has been further corroborated in the literature by studies evaluating theories of ASD, including weak central coherence (Frith, 1989; Frith & Happé, 1994; Happé & Frith, 2006) and enhanced perceptual functioning (Mottron, Dawson, Soulières, Hubert, Burack, 2006). As described earlier, the commonality between both these theories is that individuals with ASD would show better local processing (i.e. narrower focus of attention). This may then lead to superior performance on tasks requiring attention to details (e.g., embedded figures or block design tasks) to the detriment of performance on tasks that require the ability to integrate global information (e.g., a homophone reading task, in which the sentence context determines the correct pronunciation of a word) (Travers, Klinger, & Klinger, 2011).

On the other hand, while clinical observations and experimental investigations support the idea of stimulus overselectivity, there may exist a context, in which an autistic person may actually appear to have an abnormally broad focus of attention (Allen & Courchesne, 2001). Some authors offer evidence from reports of sensory sensitivities (e.g., touch, taste, smell), suggesting that these may be due to an overly broad focus and a difficulty to filter out perceptual information (Wiggins et al., 2009). Empirical evidence for an overly broad focus stems from Burack (1994), who examined the differential impact of distracter stimuli and an exogenously imposed focus (i.e., a window indicating the location on the screen in which target stimuli were presented) on attentional performance. Number of distracter stimuli was varied (0, 2, or 4) and participants had to press two different buttons when they saw one of two possible target stimuli. Autistic participants showed the greatest decrease in reaction times (RTs) in the presence of a window when no distracters were present, while RTs did not improve in the presence of the window, when distracters were present. Thus, the autistic participant's inability to focus attention optimally (i.e., their "inefficient attentional lens") was aided by the prosthethic focus, however this improvement was negated by the distracter stimuli. These findings are specifically relevant to our second study on Multiple Object Tracking.

Thus, depending on the context, individuals with ASD may have an abnormally narrow or an abnormally broad focus of attention. This variability and inconsistency in attentional focus across subjects may help elucidate certain seemingly inconsistent aspects within the clinical presentation of ASD (Allen & Courchesne, 2001). Travers et al. (2011) propose that the inconsistency of the literature may find an explanation in the fact that persons with ASD exhibit abnormalities in flexibly switching between narrow and broad focus of attention. For example, Remington, Swettenham, Campbell & Coleman (2009) found that participants with ASD had to have more distracters (i.e., a higher perceptual load) before narrowing down their focus of attention, suggesting that there may indeed be a difficulty in switching between narrow and broader focus of attention. Mann and Walker (2003) also found a deficit in broadening the spread of visual attention in ASD, as reflected by a longer delay when required to move from a small focus to a larger focus of attention. Translating these results, Burack (1994) suggests that overfocused attention may lead to the apparent lack of awareness autistic individuals seem to show for certain environmental stimuli, while a widened focus might account for their apparent overarousal and hyperstimulation by other stimuli.

5.1.2. Sustained Attention

According to Allen and Courchesne (2001), the presence of repetitive and stereotyped patterns of behavior and interests in the clinical presentation of ASD may imply that autistic individuals possess the ability to sustain attention, at least in certain contexts. Studies in autism have supported this notion, using the Continuous Performance Test (CPT), a well know measure of sustained attention and vigilance (Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956). Garretson, Fein, and Waterhouse (1990) further investigated differential effects of task difficulty and motivation on performance. They showed that task difficulty did not differentially affect performance in the autistic and comparison groups, therefore arguing against a general impairment of sustained attention in ASD. However, it was found that children with ASD performed significantly poorer in a condition, for which they received social (praise) instead of tangible (a pretzel or a penny) reinforcement. Based on these findings, Allen & Courchesne (2001) suggest that clinical reports of impaired maintenance of attention may be due to motivational and not ability-related factors.

5.1.3. Spatial Attention: Disengagement of Attention

Spatial attention has been studied in ASD using the Posner spatial target detection task (Posner, Walker, Friedrich, & Rafal, 1984), in which participants are required to fixate their eyes on a central location and to press a button when they detect a target at one of two positions along the horizontal median. Cues are introduced prior to the target's appearance, directing participants attention either to the location at which the target will appear (valid trials) or the opposite location (invalid trials). These covert shifts of spatial attention are proposed to involve three elementary operations: disengaging from the current focus of attention, moving attention to the new location, and engaging at the new location (Posner & Petersen, 1990). Compared to typical participants, a sample of autistic savants was found to have greater difficulty disengaging attention, as reflected by a larger validity effect (i.e., an increase in RT on invalid relative to valid trials (Casey, Gordon, Mannheim, & Rumsey, 1993). Wainwright-Sharp and Bryson (1993) did not find a validity effect at a short delay (100 msec), but at a long delay (800 msec), also suggesting difficulty in disengaging attention in their autism group. In a recent study, Chawarska, Volkmar and Klin (2010) found that developmentally delayed and typically developing toddlers had more difficulties disengaging visual attention from faces than had toddlers with ASD. The authors interpreted this result as an indication that toddlers with ASD are not as captivated by social stimuli, such as faces, to the same extent as toddlers without ASD and that this effect is not driven by a generalized impairment in the disengagement of attention. These most recent findings therefore bring new evidence to a seemingly well-established impairment in disengaging attention in ASD.

5.1.4. Spatial Attention: Shifting of Attention

In addition to impairments in the disengagement of attention, shifting attention from one activity to another also appears to be an area of weakness for individuals with ASD (Wainwright & Bryson, 1996). In the literature, the most common form of attentional switch is studied between a repeated stimulus and a novel stimulus within the same sensory modality (exogenous attention) (Marco et al., 2011). Research used the well-established cueing paradigm within the previously described Posner task (Posner et al., 1984). Participants are given a brief time (i.e., a cue-to-target delay) to orient to a cue and shift their attention to the possible target location. Cue-validity effects are thereafter computed through measures of RT and accuracy. Studies showed consistently that exogenous orienting is impaired in children, adolescents, and adults with ASD, as reflected by decreased cue validity effects when a peripheral cue is followed by a target (Greenway & Plaisted, 2005; Renner, Grofer Klinger, & Klinger, 2006; Townsend et al., 1999; Townsend, Courchesne, & Egaas, 1996; Townsend, Harris, & Courchesne, 1996). Other studies have examined attention shifting between modalities, and equally found impairments when shifting of attention between auditory and visual stimuli was required (Courchesne et al., 1994).

To our knowledge, no study in ASD has looked at the allocation of attention to multiple events at the same time. We were therefore interested to study this highly specific part in attentional processing by investigating how ASD individuals perform on a Multiple Object Tracking Task. Given the numerous abnormalities that were reviewed here, together with deficits in social settings and autobiographical accounts of discomfort in crowds, we expected participants to perform less well on our task.

5.2. Multiple Object Tracking

As previously mentioned, attention is a challenging concept to define. Classical theories of attention presumed a single focus of selection, however many everyday activities, such as playing video games, navigating busy intersections, or watching over children, require to pay attention to multiple regions of interest (Cavanagh & Alvarez, 2005). MOT is an experimental technique, which allows for the study of the capacity to allocate attention simultaneously to different areas in order to track multiple moving objects in a set of distracters (Pylyshyn & Storm, 1988). Observers are asked to maintain attentional focus on a limited number of preselected subgroups of elements in a dynamic scene, in which all elements interact by either bouncing off each other or occluding one another (Faubert & Sidebottom, 2012). Although precise mechanisms for this capacity are not yet established, studies have identified several characteristics of this tracking process, including such properties as defining trackable targets and the maximum number of objects, which can be tracked (Cavanagh & Alavarez, 2005). Previous studies in healthy adults have demonstrated the ability to simultaneously track four or more targets (Fougnie & Marois, 2006; Trick, Perl, & Sethi, 2005).

5.3. Models of Multiple Object Tracking

Four different models of Multiple Object Tracking are briefly described, including preattentive indexes (FINST), grouping, attention switching, and multifocal attention. Pylyshyn and colleagues were the first to develop the MOT task (Pylyshyn & Storm, 1988), in order to investigate how the visual system tracks multiple moving objects. In their FINST (for FINgers of INSTantiation) model, it was suggested that multiple elements have multiple indexes (Pylyshyn, 1994; Pylyshyn & Storm, 1988), with a total of four to five indexes or pointers in the visual system that would each pick out and stay attached to individual objects to be tracked. These indexes are thought to be independent of each other, and therefore allow for the simultaneous tracking of multiple objects. The maximum number of objects to be tracked depends on the number of indexes. This FINST model was followed by the grouping theory proposed by Yantis (1992), which suggested that all targets were grouped into one higher order object with each target being part of a virtual polygon. According to this theory, tracking one changing shape would then require a single attentional channel, and targets would group more strongly and tracking becomes easier, when these share common motion. Like in the grouping model, a single focus of attention is also required in the attention switching model (Yantis, 1992; Pylyshyn & Storm, 1988; Oksama & Hyöna, 2004). This single focus would cycle rapidly through the targets, indexing their locations and returning to each before it moves too far away. Thereafter, the nearest item would be taken as the new position of the target, which would be stored for the next cycle. Recent findings however have ruled out both the grouping and switching theories (Alvarez & Cavanagh, 2005). Finally, the last model to be proposed and the one that is most commonly accepted proposes that multifocal attention mechanisms are required to process information related to the tracking of multiple moving objects (Cavanagh & Alvarez, 2005). According to this latest theory, each target attracts an independent focus of attention and these follow the targets as they move. At the end of a tracking trial, participants are still attending to the same items they started out with (now in different locations) and they are then able to identify them as being part of the original set. Whereas the FINST theory proposes that the tracking aspect of MOT is automatic and non-attentional (Pylyshyn, 1994; Pylyshyn & Storm, 1988), the model of multifocal attention presumes the involvement of classic properties of attention, however which require that attention can deploy more than one focus (Cavanagh & Alvarez, 2005).

Notwithstanding the mechanisms underlying the capabilities to track multiple moving objects, and to allocate attention to various areas at the same time, these abilities are of utmost importance in our everyday life. While we are not faced with the choice to integrate information from multiple sensory modalities at the same time, we are equally not spared multiple events happening around us simultaneously. Considering the numerous autobiographical accounts by autistic individuals of unease in crowds and other dynamic environments (e.g., Grandin, 1996, Williams, 1994), and in our search for a deeper understanding of this condition, it appears crucial to evaluate this capacity that is essential to navigate everyday life. In the same way that functional mechanisms of multisensory integration aid in the apparently automatic merging of information, functional mechanisms of multifocal attention may help attend to multiple events in our life without feeling overwhelmed.

5.4. 3-D Multiple Object Tracking

In order to increase the ecological validity of our task, we decided to use a virtual reality setting, described in the following chapter, to study 3D-MOT capacities. Further, instead of looking at number of objects tracked, we employed a measure of speed thresholds, which is the greatest speed at which observers can track the moving targets. To date, no other group has investigated MOT capacities in autism. Based on findings of impairments in attention processing in ASD and research showing that healthy adults are generally able to track four spheres, whereas older adults seem to be limited to three under standard conditions (Trick et al., 2005), we chose a maximum of three spheres to be tracked in our study. Also given previous findings of attention deficits in ASD, especially with regards to an overly broad focus, we expected individuals with ASD to perform worse on both our conditions, the single- object tracking condition and the multiple-object tracking condition. However, we expected ASD participants to perform worse on the multiple-object tracking condition due to increased levels of complexity inherent in this task.

5.5. Multiple Object Tracking and the Brain

Research investigating brain mechanisms involved in the MOT task found it to be an attention demanding task, engaging extensive frontal and parietal areas (Culham, Brandt, Cavanagh, Kanwisher, Dale, & Tootell, 2001). Jovicich and colleagues used functional brain imaging to investigate the neural basis for attentional load in a classic Multiple Object Tracking paradigm (Jovicich, Peters, Koch, Braun, Chang, & Ernst, 2011). While measuring brain activity as subjects tracked a variable number of moving targets, the authors found linear increase of brain activity with number of balls tracked. This activity was primarily observed in the posterior parietal areas, including the intraparietal sulcus (IPS) and superior parietal lobule (SPL).

Chapter 6. Article 2

3D-Multiple Object Tracking in Autism

Eva-Maria Hahler, Laurent Mottron, Jocelyn Faubert

Autism Research, *in revision.*

6.1. Abstracts

Lay Abstract

Previous research has shown that autistics show deficits in certain tasks involving movement and attention. In our everyday life, we are constantly exposed to complex visual environments in which we have to track and integrate numerous moving objects in our visual field at the same time. Multiple Object Tracking (MOT) is the capacity to allocate attention simultaneously to different areas in order to track multiple moving objects. Given previous difficulties found in autism with regards to tasks involving movement and attention, we could presume that the capacity to track multiple moving objects, a task often performed in daily activities, might be diminished in this population. To test this prediction, fifteen autistic and fifteen comparison participants were asked to track one or three moving targets within a total of eight moving objects in a virtual reality environment. Performances were measured based on speed thresholds, which evaluates the greatest speed at which observers are capable of successfully tracking moving objects. Autistics displayed overall reduced speed thresholds, whatever the number of spheres to track. These findings extend previous results of attention difficulties in autism, showing that autistics have difficulty directing their attention to multiple areas at the same time. A difficulty in this task may reflect a person’s everyday life capacities to interact with a dynamic environment.

Scientific Abstract

Autobiographical accounts by autistic persons report of unease in everyday tasks that require the allocation of attention simultaneously to different areas. In laboratory settings, autistics present with impaired movement processing in some tasks. We therefore expected that performance in a task combining attention and dynamicity, Multiple Object Tracking or MOT, might be diminished in autism. To test this prediction in an ecologically valid setting, fifteen autistic and fifteen IQ-matched comparison participants were asked to track one or three moving targets within a total of eight moving objects in a virtual reality environment. Performances were measured based on speed thresholds, which evaluates the greatest speed at which observers are capable of successfully tracking moving objects. Autistics displayed overall reduced speed thresholds, whatever the number of spheres to track. In contrast there was no group x sphere number interaction, i.e. the number of targets to track did not affect differentially the two groups of participants. These findings extend previous results of altered attention mechanisms in autism with regards to the simultaneous allocation of attention to multiple areas. A difficulty in this task may reflect a person's everyday life capacities to interact with a dynamic environment.

Key words: Autism, Multiple Object Tracking, speed thresholds, visual perception, attention

6.2. Introduction

"Where someone else may have seen 'crowd', I saw arm, person, mouth, face, hand, seat, person, eye… I was seeing ten thousand pictures to someone else's one." (Williams, 1998). "When I was a child, large noisy gatherings of relatives were overwhelming, and I would just lose control and throw temper tantrums." (Grandin, 1996). Autobiographical accounts like the ones cited above by autistic individuals frequently report of discomfort in dense social situations such as in crowds, reflecting difficulties in sensory processing with possible underlying perceptual origins. In our everyday life, we are unrelentingly exposed to complex visual environments in which we have to concurrently track and integrate multiple moving objects in our visual field. For instance, while walking in the street, it is necessary to attend and spatially integrate moving targets such as cars or pedestrians. In such environments, perceptual integration of dynamic visual targets is not only fundamental in order to produce good decision-making processes and appropriate motor responses, but also in order to understand and interpret social situations.

Multiple Object Tracking (MOT) is the capacity to allocate attention simultaneously to different areas in order to track multiple moving objects (Pylyshyn & Storm, 1988). It is a perceptual-cognitive task that links low-level attentional processing with high-level cognitive demands, integrating at the same time aspects of visual and motion perception. Based on autobiographical accounts of unease in many natural and everyday tasks that require MOT-type capacities (e.g., following a conversation, tracking people in a crowd, traveling to another city) and on research findings of altered visually-related information processing in autism (e.g., Dakin &

Frith, 2005; Simmons et al., 2009; for reviews), we could presume that the capacity to track multiple objects would be different, and plausibly diminished for this population. The purpose of the present research was thus to evaluate MOT capacities in autistic individuals in a virtual environment, in order to determine whether previous findings of anomalies in attention and motion processing are paralleled in this ecological task and whether they might explain, at least in part, the discomfort autistic people often report in complex dynamic scenes such as in crowded environments.

There is some controversy in the empirical evidence regarding motion processing in Autism Spectrum Disorders (ASD). The literature on motion perception in autism reveals alterations in dynamic processing (e.g., Spencer et al., 2000; Milne et al., 2002; Bertone et al., 2003); however conflicting results make it difficult to fully interpret the existing data (e.g., Pellicano et al., 2005; Del Viva et al., 2006). Current findings on biological motion seem to be consistent with a low-level difficulty with motion processing in autism (Simmons et al., 2009). Recent research on MOT generally proposes that multifocal attention mechanisms are necessary to process such information (Cavanagh & Alvarez, 2005), whereas studies on attentional processes in autism also suggest a heterogeneous profile of attentional abilities (for a review, see Allen & Courchesne, 2001), revealing on the one hand deficits in attention shifting (Courchesne et al., 1994; Landry & Bryson, 2004), broadening the spread of visual attention (Mann & Walker, 2003), and encoding multiple elements in complex visual scenes (Loth et al., 2008; O'Hearn et al., 2011), whilst on the other hand showing superiority in discriminating elementary visual information within a visual search paradigm (O'Riordan & Plaisted, 2001) as well as in disengaging attention from social targets (Chawarksa et al., 2010).

The literature shows that typical individuals can generally track four or sometimes five elements depending on the condition (Fougnie & Marois, 2006; Alvarez & Franconeri, 2007). In the present research, instead of looking at number of objects tracked, we aimed to increase the ecological aspect of our task and therefore decided to use a virtual reality setting to study 3D-MOT capacities, employing a measure of speed thresholds that is the greatest speed at which objects can be tracked. Previous research has established the various advantages of using speed thresholds as a dependent variable to study MOT capacities, such as variation of values on a continuous ratio scale and better discrimination of performances between observers who are able to track the same number of elements (Faubert & Sidebottom, 2012). It has also been shown that using a 3D- versus a 2D-environment during an MOT task is advantageous in obtaining superior speed thresholds and that it therefore constitutes the ideal setting to optimally measure MOT performance as it most conforms to our everyday reality (Tinjust et al., 2008).

Interestingly, Temple Grandin (2008) suggests that some of the social deficits observed in autism may be explained by the inability of autistic individuals to quickly shift attention, which may prevent them from catching the short, silent messages that people frequently use to communicate. It is therefore more relevant to study the quality and function of these tracking processes by means of an ecological approach than to focus on the quantitative aspects of how many objects can be tracked, if we want to further our understanding of how autistic people function in everyday life and potentially help improve this quality of life.

6.3. Method

Participants

Fifteen autistic individuals with normal intelligence (average Wechsler FSIQ = 105.8, SD =12.4) were recruited from a specialized clinic for autistic people. A diagnosis of autism was obtained using the algorithm of the Autism Diagnostic Interview (ADI) (Lord et al., 1994) combined with the Autistic Diagnostic Observation General (ADOS-G) except for two participants for which diagnosis was obtained through ADOS-G and non-standardized clinical retrospective interrogation only (Lord et al., 2000), both of which were conducted by a trained researcher (L.M.) who obtained reliability on these instruments. All autistic participants had a score above the ADI/ADOS (or the ADOS-G only for two of them) cut-off in the four areas relevant for diagnosis (social, communication, restricted interest and repetitive behaviours, and age of symptom onset). Fifteen typically developing participants were recruited from the community as a comparison group. These were screened for a past or current history of psychiatry, neurological, or other medical disorder and all had a typical academic background and development (mean IQ = 108.1, SD = 9.5). The groups were matched as closely as possible in terms of gender (+/- 0), chronological age (+/- 5), and full-scale IQ (+/- 12) (Table 1). The mean chronological age of the comparison and autism groups was 24.1 (SD = 4.1) and 22.7 (SD = 4.1) respectively. All participants had normal or corrected-to-normal vision (20/20 Snellen acuity for both eyes) and binocular vision, as evaluated by a Randot Stereotest (Stereo Optical Co.), and were not taking medication at the time of participation. Informed written consent was obtained from all participants. The research was prospectively reviewed and approved by a duly constituted ethics committee.

Insert Table 1 about here

Materials

Environment. A fully immersive virtual environment (C.A.V.E., Fakespace technology) was used in which our stimuli were presented (Figure 1). This 8x8x8 feet environment is composed of four projection surfaces (three walls and the floor) on which images were projected in stereo. Participants wore liquid crystal shutter stereoscopic goggles (Stereographics, San Rafael, CA) that enable 3D stereoscopic perception. Images were rendered with a refresh rate of 48 Hz in stereo and goggles were shuttered at 96 Hz to deliver 48 images per second to right and left eyes. A magnetic captor (Flock of birds, Ascension technology corp., Burlington, VT) was set on the goggles in order to track head position and to correct in real-time the visual perspective relative to the head position. A computer (Silicon graphics 540) was used to generate the stimuli and record participants' responses.

Insert Figure 1 about here

Stimuli. A virtual cube containing eight yellow spheres was used to display the stimuli. The anterior side of the cube measured 42° of visual angle and the center of the cube was positioned at 67 cm from participants’ eyes. The sides and edges of the cube were transparent, therefore invisible for the participants. A black fixation spot (0.6 degree of visual angle and presented at 67cm from participants' eyes) was presented at the center of the cube. When animated, the eight spheres could collide between each other and within the limits imposed by the virtual cube. The initial spheres’ locations and motion directions were randomly determined. Sphere velocity remained constant within each tracking phase, but changed from trial to trial depending on the participant's response. During the experiment, stimuli were displayed in the following sequence (Figure 2): (A) *Presentation phase*, in which eight yellow spheres were presented in the virtual cube for 3 seconds in a random position, with a spatial restriction of 2 cm between each sphere. (B) *Indexation phase*, in which among the eight spheres and according to the condition, one or three spheres turned red for 2 seconds in order to be identified as the target(s). Afterwards, these spheres reverted to their initial color (yellow). (C) *Tracking phase*, in which the eight yellow spheres moved for 6 seconds and then stopped. (D) *Response phase*, in which each sphere was associated with a number from one to eight. Participants were asked to give the numbers of the spheres that they had formerly identified as the target(s). *Feedback phase*, during which the target or the three targets formerly indexed turned red for 3 seconds to give the participant feedback about his answer.

Design and Procedure

Tracking conditions. Two tracking conditions were used. The *single-object tracking condition* required participants to track a single moving sphere among eight moving spheres. The *multiple-object tracking condition* required participants to track three moving spheres among eight moving spheres.

Insert Figure 2 about here

Participants were seated on an ophthalmologic chair. The chair height was adjusted in order to put participant gaze at 67cm from the fixation spot and 160cm from the floor. Participants were asked to wear stereo goggles and to focus their gaze on a black fixation spot (0.6° of visual angle), located at the center of the virtual cube, while tracking either one or three spheres identified as target. After each tracking phase within one trial, participants verbally identified the sphere or the three targets spheres, yielding one threshold per trial. Answers were entered in the computer by the experimenter after each tracking phase, although it would have been best to record participant's verbal responses to avoid mistakes instead of the experimenter entering data during the task. Feedback was then visually provided to participants, in the form of the target spheres turning red again. A practice trial was completed prior to experimental trials, in order to allow for proper familiarization with the task. The experimental conditions (single-object tracking and Multiple Object Tracking) were presented 3 times each (for a total of six trials). Trials lasted approximately 8 min each, depending on the time necessary to obtain the participant’s threshold, with a break of 15 min after completion of half of the trials. The initial single- vs. multiple-object tracking condition was randomly chosen and the successive perceptual conditions were alternated. In each tracking condition, participants' performance was calculated by averaging the results obtained on the three trials administered.

Measures

Adaptive staircase. An adaptive staircase protocol (one down/one up) (Levitt, 1971) was used in order to adjust the speed of the moving spheres between tracking instances relative to the subject's answer (initial spheres speed was 2,5 cm/sec). The staircase was set to eight inversions and speed thresholds were calculated from the last four reversals. Before the second inversion the speed of the spheres was increased (correct answer) or decreased (wrong answer) by a factor of 0.2 log unit at each trial. From the second inversion to the fourth inversion, the speed of the spheres was changed by a factor of 0.1 log unit in the subsequent trial. The speed of the spheres then changed by a factor of 0.05 log unit in the subsequent trials. A correct answer was considered as the identification of all the targets. All other responses were considered false. Speed thresholds, measured in cm/sec, established the greatest speed at which participants were able to track the moving objects (Table 2).

Insert Table 2 about here

6.4. Results

3D-Multiple Object Tracking in Autism

Figure 3a shows speed thresholds for autistic and TD individuals for the single-object tracking condition and Figure 3b shows speed thresholds for both groups for the multiple-object tracking condition. A 2 x 2 split-plot ANOVA (group (between) x tracking number (within)) revealed a significant main effect of group (*F* [1, 28] = 6.96, $p < .05$, $\eta 2 = .20$), demonstrating that whatever the condition, autistic participants were generally less able to track the spheres in comparison to matched comparison participants. A significant main effect of tracking number (*F* [1, 28] = 243.66, $p < .001$, $\eta^2 = .90$) was found and a priori contrast measures showed that both groups performed significantly better (i.e. showed higher speed thresholds) in the single-object tracking condition (*M* = 1.74, *SD* = 0.10) than in the multiple-object tracking condition (*M* = 1.41, *SD* = 0.15), *t* (27) = 1.57, $p < .001$, $d = 2.59$. No significant group x tracking number interaction was found, *F*(1, 28) = 1.30, $p > .05$, $\eta 2 = .04$.

Insert Figure 3 about here

6.5. Discussion

Summary of findings. The present study used a virtual reality environment to assess 3D-MOT capacities in autistic and typically developing individuals. Autistic as well as typically developing individuals performed better when asked to track one than three spheres in a set of distractors, as reflected by higher speed thresholds found in both groups on the single-object tracking condition. This indicates that the interpretation of our findings is not contaminated by floor or ceiling effects, with increase in task difficulty being detrimental to performance. Our main finding is that autistic individuals were less able than typical individuals to track one or three spheres in a set of distractors, as measured by reduced speed thresholds on both conditions.

Relation with previous findings on movement processing in autism. Alterations exist at multiple levels of visual perception in autism. Alterations have been found both in low-level visual processing (e.g., Milne et al., 2002; Bertone et al., 2005), as well as on high-level visual tasks (e.g., Shah & Frith, 1993, Caron et al., 2006), generally reflecting superior performances on tasks requiring local or detailed processing of visuo-spatial information while finding a decreased ability for the processing of more complex types of information requiring an *integrative, dynamic or global* analysis, as for example interpreting biological motion stimuli such as human point-like walkers (see Dakin & Frith, 2005; Mottron et al., 2006; Simmons et al., 2009 for reviews). However, the initial, prevailing message "static is superior, dynamic is impaired" is less clear now, with a large body of typical results in movement perception (Simmons et al., 2009), and recently, even findings of superiority in a dynamic task (Foss-Feig et al., 2012). Despite this confusing picture, our results, showing a decreased performance in both object tracking conditions, demonstrate a robust deficit. Our findings, in a task requiring the focus on multiple objects or events at the same time within a large field, are therefore in line with alterations in processing dynamic information observed in autistic individuals (e.g., Spencer et al., 2000; Milne et al., 2002; Bertone et al., 2003).

Relation with previous findings on attention mechanisms in autism. Previous research has shown that multifocal attention mechanisms are necessary to process MOT-type information (Cavanagh & Alvarez, 2005). The literature on attentional processes in autism predominantly reveals difficulties in attention shifting (Courchesne et al., 1994; Landry & Bryson, 2004), broadening the spread of visual attention from local to global (Mann & Walker, 2003) and encoding multiple elements in complex visual scenes (Loth et al., 2008; O'Hearn et al., 2011). However, superiorities have been found in discriminating elementary visual information within a visual search paradigm (O'Riordan & Plaisted, 2001). The fact that autistic participants were less able than typical individuals to track a single or multiple objects in a set of distractors may corroborate findings of a deficit in broadening the spatial spread of visual attention or of difficulty in attention shifting, although shifting attention and simultaneously maintaining one or more events in focus have to be distinguished. The first has to do with difficulties in the disengagement of attention (Courchesne et al., 1994) or with overfocused attention (Lovaas et al., 1979), a characteristic observed in some tasks but not others in autism (Chawarksa et al., 2010). However, our task did not so much measure a shift in attention but rather the maintenance of focus on one or more elements at the same time in the presence of distractors. The processes involved in performing well on the 3D-MOT task implicate a minimizing of attention shifting, as well as an optimizing of the view through a better distribution of attention, be it that the participant has to follow one or multiple objects. Hence, our findings extend previous findings of altered attention mechanisms with regards to the allocation of attention to one or more dynamic events.

Ecological validity of the task. The paradigm used in the present study is novel in that MOT-capacities were not simply measured as a function of number of tracked objects, an approach that focuses on end results only, but combine number and movement of the targets to be tracked. Hence, by assessing the greatest speed at which observers were able to track moving objects, transferability and applicability to real life situations are much more warranted. Our measure provides for a better discrimination of performances between observers who are able to track the same number of elements (Faubert & Sidebottom, 2012), which is what we observed in our study as well, since both groups were able to track one and three elements, however not at the same velocity. In addition, the trajectory path of the moving elements can be quite unpredictable with sudden changes in direction and shape with numerous occlusions and segmentations such as objects blocking the view of others or disappearing from view for an instance. We can then suppose that if we find difficulties on the MOT task, this may be reflective of difficulties in a person's everyday life capacities to interact with their environment. Lower performances in terms of speed may for example be indicative of the speed at which a person is able to follow a conversation or is comfortable in travelling from one place to another, e.g. walking down for instance the alley of a busy shopping mall. During the MOT-task itself, the rapidity at which all of these tasks have to be performed increases exponentially as a function of the participant's answer. Unfortunately, this is not the case in our everyday reality and surroundings. As we walk across a shopping mall, the speed of events happening around us does not increase or decrease as a function of our capacity to be able to follow them but well despite this capacity. We can therefore easily imagine that autistic individuals may be at a disadvantage if they were indeed, as shown in our study, not able to attend to one or multiple events as rapidly as typical individuals. Public settings and dynamic environments do not slow down for them, and we will therefore have to start thinking about how we can help bridge these difficulties in the future.

Applicability to social settings. Our findings that autistic individuals show difficulties in allocating their attention as rapidly as typical individuals to one or more dynamic events may generate new possible explanations for social symptoms, as reported in autobiographical accounts of discomfort in social situations such as in crowds (Grandin, 1992). Thus, difficulties on our task may help elucidate struggles that autistic individuals might experience when finding themselves amongst a group of people, as for example in a shopping mall or in a school environment. This finding, despite being obtained in a non-social task, may not only be valid with regards to dynamic visual environments such as crowds, but, beyond difficulty in shifting attention (Grandin, 2008), also have an impact in following several nonverbal cues between persons having a conversation.

Future directions. Future research using virtual reality environments will permit us to create even more ecological paradigms, for instance the reconstruction of real-life settings and social situations such as crowd dynamics in malls, schools or public transport. For the purpose of the present research, the next step could be for example to ask participants to track single or multiple events embedded in a social situation, in order to see if performances remain the same, or if the social aspects of the situation may interfere with them. Research has shown the applicability of training in MOT-type capacities in the coaching and rehabilitation of high-level athletes (Faubert & Sidebottom, 2012). Hence, in the future, it might be important to understand if this was also an option for autistic individuals and see if they could potentially benefit from such training. If this was the case, it might evidently be worthwhile to train this capacity, in order to improve their quality of life.

6.6. Acknowledgements

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6.7. References

Allen, G., & Courchesne, E. (2001). Attention function and dysfunction in autism. Frontiers in Bioscience, 6, D105-119.

Alvarez, G. A., & Franconeri, S. L. (2007). How many objects can you track? Evidence for a resource-limited attentive tracking mechanism. Journal of Vision, 7(13), 14 11-10.

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

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

Caron, M. J., Mottron, L., Berthiaume, C., & Dawson, M. (2006). Cognitive mechanisms, specificity and neural underpinnings of visuospatial peaks in autism. Brain, 129(7), 1789-1802.

Cavanagh, P., & Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. Trends in Cognitive Science, 9(7), 349-354.

Chawarska, K., Volkmar, F., & Klin, A. (2010). Limited attentional bias for faces in toddlers with autism spectrum disorders. Archives of General Psychiatry, 67(2), 178-185.

Courchesne, E., Townsend, J., Akshoomoff, N. A., Saitoh, O., Yeung-Courchesne, R., Lincoln, A. J., et al. (1994). Impairment in shifting attention in autistic and cerebellar patients. Behavioral Neuroscience, 108(5), 848-865.

Dakin, S., & Frith, U. (2005). Vagaries of visual perception in autism. Neuron, 48(3), 497-507.

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

Faubert, J., & Sidebottom, L. (2012). Perceptual-cognitive training of athletes. Journal of Clinical Sports Psychology, 6, 85-102.

Foss-Feig, J., Cascio, C., Schauder, K., & Tadin, D. (2012). A substantial and unexpected engancement of motion perception in children with autism spectrum disorders. Poster session presented at the meeting of Vision Science Society, Naples, FL.

Fougnie, D., & Marois, R. (2006). Distinct capacity limits for attention and working memory: Evidence from attentive tracking and visual working memory paradigms. Psychological Science, 17(6), 526-534.

Grandin, T. (1992). An inside view of autism. In Schopler & Mesibov (Eds.), High-functioning individuals with autism (pp. 105-126). New York: Plenum Press.

Grandin, T. (2008). The way I see it. A personal look at autism and Asperger's. Arlington: Future Horizons.

Grandin, T. (1996). Thinking in pictures and other reports from my life with autism. New York: Doubleday. 64 p.

Landry, R., & Bryson, S. E. (2004). Impaired disengagement of attention in young children with autism. Journal of Child Psychology and Psychiatry, 45(6), 1115-1122.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. Journal of the Acoustical Society of America, 49(2, Pt. 2), 467-477.

Loth, E., Carlos Gomez, J., & Happé, F. (2008). Detecting changes in naturalistic scenes: contextual inconsistency does not influence spontaneous attention in high-functioning people with autism spectrum disorder. Autism Research, 1(3), 179-188.

Lovaas, O. I., Koegel, R. L., & Schreibman, L. (1979). Stimulus overselectivity in autism: a review of research. Psychological Bulletin, 86(6), 1236-1254.

Mann, T. A., & Walker, P. (2003). Autism and a deficit in broadening the spread of visual attention. Journal of Child Psychology and Psychiatry, 44(2), 274-284.

Milne, E., Swettenham, J., Hansen, P., Campbell, R., Jeffries, H., & Plaisted, K. (2002). High motion coherence thresholds in children with autism. Journal of Child Psychology and Psychiatry, 43(2), 255-263.

Mottron, L., Dawson, M., Soulieres, I., Hubert, B., & Burack, J. (2006). Enhanced perceptual functioning in autism: an update, and eight principles of autistic perception. Journal of Autism and Developmental Disorders, 36(1), 27-43.

O'Hearn, K., Lakusta, L., Schroer, E., Minshew, N., & Luna, B. (2011). Deficits in adults with autism spectrum disorders when processing multiple objects in dynamic scenes. Autism Research, 4(2), 132-142.

O'Riordan, M., & Plaisted, K. (2001). Enhanced discrimination in autism. Quarterly Journal of Experimental Psychology. A, Human experimental psychology, 54(4), 961-979.

Pellicano, E., Gibson, L., Maybery, M., Durkin, K., & Badcock, D. R. (2005). Abnormal global processing along the dorsal visual pathway in autism: a possible mechanism for weak visuospatial coherence? Neuropsychologia, 43(7), 1044-1053.

Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: evidence for a parallel tracking mechanism. Spatial Vision, 3(3), 179-197.

Simmons, D. R., Robertson, A. E., McKay, L. S., Toal, E., McAleer, P., & Pollick, F. E. (2009). Vision in autism spectrum disorders. Vision Research, 49(22), 2705-2739.

Shah, A., & Frith, U. (1993). Why do autistic individuals show superior performance on the block design task? Journal of Child Psychology and Psychiatry, 34(8), 1351-1364.

Spencer, J., O'Brien, J., Riggs, K., Braddick, O., Atkinson, J., & Wattam-Bell, J. (2000). Motion processing in autism: evidence for a dorsal stream deficiency. NeuroReport, 11(12), 2765-2767.

Tinjust, D., Allard, R., & Faubert, J. (2008). Impact of stereoscopic vision and 3D representation of visual space on multiple object tracking performance. Journal of Vision, 8(6), 509.

Williams, D. (1998). Autism and Sensing. The Unlost Instinct. London: Jessica Kingsley Publishers. 21 p.

6.8. Tables, Legends & Figures

Table 1.

Participant Characteristics For Autistic and Comparison Participants

Participant Characteristics	Autistic Participants	Comparison Participants
Number	15	15
Age (y:m)		
Mean	22:7	24:1
SD	4.1	4.1
Range	18.0-33.0	19.0-34.0
FSIQ		
Mean	105.8	108.1
SD	12.4	9.5
Range	91-126	92-121

Table 2.

Mean Speed Thresholds Expressed in Terms of Log Speed Sensitivity (±SD) For Each Group and Tracking Condition.

Tracking condition	Autistic participants	Comparison participants
Single-Object Tracking	1.699 (0.111)	1.775 (0.060)
Multiple-Object Tracking	1.345 (0.152)	1.470 (0.133)

Figure Legends

Figure 1. Illustration of the Multiple Object Tracking Environment in the CAVE.

Figure 2. Illustration of the Multiple Object Tracking Sequence: (A) presentation, (B) indexation, (C) tracking, (D) response.

Figure 3. Mean speed thresholds for single- and multiple-object tracking conditions for autistic and comparison participants. Bars represent the standard error of the mean (SEM).

Figure 1.

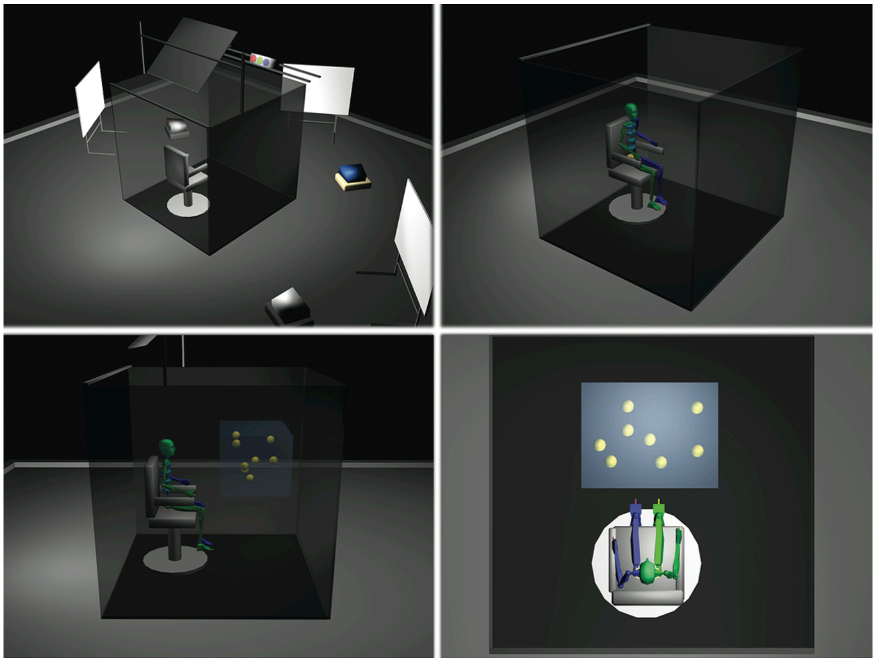


Figure 2.

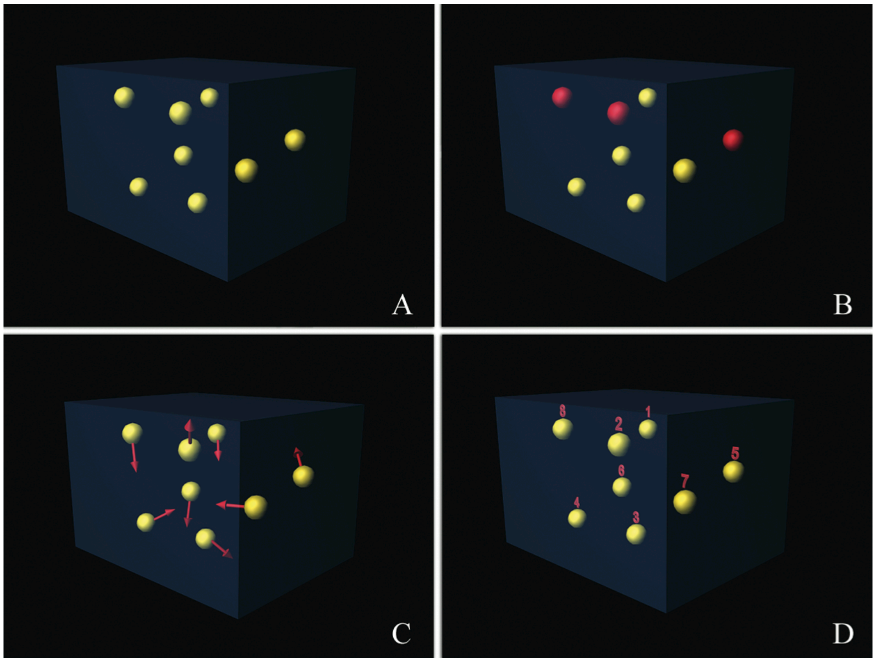
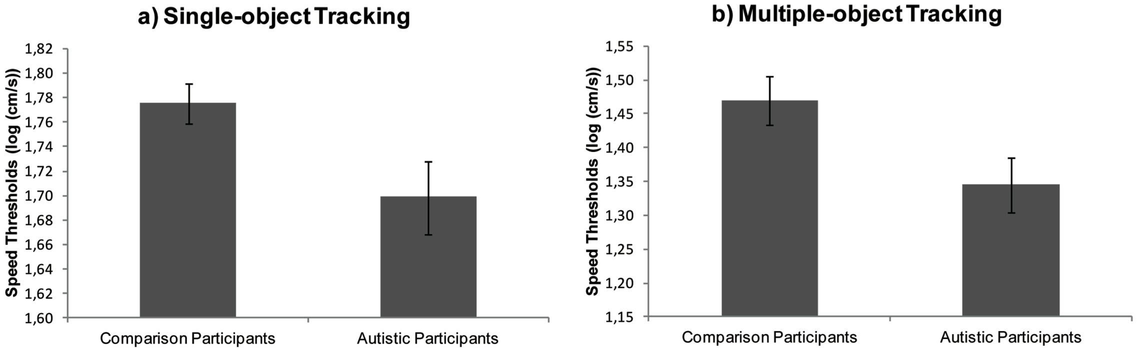


Figure 3.


a) Single-object Tracking
Speed Thresholds (log (cm/s))
1,82
1,80
1,78
1,76
1,74
1,72
1,70
1,68
1,66
1,64
1,62
1,60
Comparison Participants
Autistic Participants
b) Multiple-object Tracking
Speed Thresholds (log (cm/s))
1,55
1,50
1,45
1,40
1,35
1,30
1,25
1,20
1,15
Comparison Participants
Autistic Participants

Chapter 7. General Discussion

In this final chapter, we will briefly summarize the results of the two completed studies, followed by a general discussion of these findings within the framework of our current knowledge of autism. The discussion is opened by considering alterations in unisensory versus multisensory processing as well as attentional anomalies in ASD, followed by the discussion of the role of these processes as primary impairments underlying atypical behaviours in ASD. After these major points, we explore the findings in relation to anomalies in brain structure and brain regions potentially involved in our tasks, and how they may relate to each other. Thereafter clinical implications are discussed, as well as future directions, including the potential impact of our studies on intervention and for the development of novel therapies.

7.1. Summary of findings

In two separate studies, we presented the first assessment of visuo-tactile size discrimination in children with ASD, as well as the first investigation of 3D-Multiple Object Tracking capacities in autistic adults. For both studies, we were able to extend previous findings in autism research. First, we expanded the literature on MSI in ASD, extending results of alterations in multisensory processing and the development thereof to the visuo-tactile domain. Autistic children performed less well and showed no maturational effects, compared to controls, on unisensory and multisensory conditions. Second, we extended previous findings of anomalies in attentional mechanisms with regards to the use of multifocal attention, showing that autistic adults, compared to controls, were less able to track one or multiple objects in a set of distracters.

7.2. Alterations in Unisensory vs. Multisensory Processing in ASD

Less than a decade ago, the beginning of a shift was observed in autism research, away from the study of the senses in isolation towards the exploration of the interaction between senses. While this was a crucial shift, as we still know very little about MSI in ASD, our studies have demonstrated the equal importance of continuing to investigate sensory modalities in isolation. Further, our findings showed that sensory processing remains an important topic to be considered in autism research, thus going in the same direction as the changing diagnostic criteria for the condition.

Previous behavioural studies have yielded mixed results with regards to impairments in multisensory processing in ASD. One explanation for these differences is that anomalies are largely found on tasks involving higher-order stimuli such as language or socially relevant stimuli (e.g., Bebko et al., 2006; Mongillo et al., 2008), and less frequently on tasks involving low-level stimuli (e.g., van der Smagt et al., 2007). Another possibility is that the relative timing of input to be integrated plays an important role in the consideration of differences in multisensory processing in individuals with ASD (David, Schneider, Vogeley, & Engel, 2011). This is supported by findings of impairments on low-level tasks involving flashes and beeps, where children with ASD were able to integrate multisensory inputs, but did so over longer periods of time (Foss-Feig et al., 2010; Kwakye et al., 2011). Electrophysiology studies showed similarly that integration is happening at a later stage in children with ASD in a passive auditory-somatosensory task (Russo, Foxe, Brandwein, Altschuler, Gomes, & Molholm, 2010), however not in an active audio-visual task (Brandwein et al., 2012). The latter authors (Brandwein et al., 2012) suggest the discrepancies between these two studies to be due either to the different sensory modalities involved or to differences in the allocation of attention. Whereas participants were asked to ignore the stimuli while watching an unrelated movie in the auditory-somatosensory study, they were required to attend and make a response to the stimuli in the audio-visual study. Brandwein et al. (2012) therefore propose that individuals with ASD may need to actively attend stimuli in order for early MSI to occur, whereas this does not seem to be the case for controls. Notwithstanding the precise underlying mechanisms, these findings together indicate that there is a decrease in the extent of the automatic integration of sensory inputs in children with ASD compared to children with TD (Brandwein et al., 2012).

An additional explanation for discrepancies in MSI may find its origin in alterations at the unisensory input level. Early studies of MSI in autism did not include measures of unisensory processing when investigating multisensory abilities (e.g., Bebko et al., 2006), thus making it difficult to conclude to a unique multisensory deficit and leaving the question open if difficulties in unimodal processing might have impacted the results. Others concluded to a unique impairment in MSI after having controlled for unisensory impairments in lip reading (Smith & Bennetto, 2007) or visual accuracy (Taylor et al, 2010). However, unimodal sensory differences were also found between ASD and TD groups in both these studies. It is therefore not entirely possible to exclude their influence on deficits in multisensory processing. The hypothesis that unisensory processing skills may strongly impact on MSI abilities is further corroborated by findings, where individuals with ASD benefitted from training in the unimodal condition and successful transfer was shown from the unisensory condition to the multisensory condition (Williams et al., 2004). Our study also revealed deficits in unisensory processing, in both the visual and tactile modalities, to impact the overall integration between modalities, with the tactile processing constituting the limiting factor for ASD participants' performance. This is supported by findings of previously mentioned electrophysiological studies. In both these studies, alterations were found in children with ASD compared to TD participants on measures of MSI, however, significant differences between these groups were also obtained in unisensory event-related potentials (ERPs) (Brandwein et al., 2012; Russo et al., 2010).

For future studies on MSI, it therefore appears important to continue to carefully control for unisensory abilities in individuals with ASD, as an anomaly at the unisensory entry level may evidently influence the integration of multiple senses. When designing tasks in MSI, it is also important to take into account previous research completed on the senses in isolation. For example, in our first study, we obtained results in line with findings of visual dominance on a size discrimination task (e.g., Miller, 1972; Power & Graham, 1976) in our typical sample, however not in individuals with ASD. We believe that decreased performance on our unisensory condition may have been influenced by the fact that our task asked participants to make a spatially distributed comparison. This would be in line with previous findings in autism of enhanced performance to the processing of details versus decreased performance when required to make a global analysis (e.g., Mottron & Burack, 2006; Happé & Frith, 2006). Finally, while we did not measure MSI in our second study on MOT, we also found alterations in unisensory processing on this task, in which autistic adults performed less well on both conditions, hence demonstrating diminished performance within one modality.

7.3. Development of Sensory Processing Skills in ASD

In our first study, we replicated previous findings in typical development that found visuo-tactile abilities to continue to develop through the school years until 8-14 years of age (Gori et al., 2008). While we observed a significant development of visual abilities over time in typical development, this was not the case in autistic children. Similarly, we found a significant difference in maturation of multisensory processing skills between groups. This is in line with the few other studies, which have examined the development of multisensory processing in ASD, showing either delayed or completely diminished performance in the autism group. Findings from the most recent study showed that children with ASD integrate even very basic, nonsocial audio-visual stimuli differently and less effectively than children with TD (Brandwein et al., 2012). Considering effects of developmental cascades, alterations at this basic level may then have an impact on several other levels of information processing. Our study therefore confirmed the great importance of understanding how these sensory processing abilities develop over time in ASD as this influences our understanding of their core symptoms, including their atypical sensory behaviours.

Given our previous argument that it is equally important to consider unisensory abilities, we also need to pay attention to the development of these abilities over time, especially as we did not observe any maturation effects in unisensory modalities in the ASD group, whereas this was the case in the TD group. Further, significant effects in maturation in multisensory processing skills were largely driven by the respective unisensory abilities in both groups. This is consistent with previous findings showing delay in audiovisual integration, however also in visual accuracy (Taylor et al., 2010).

Thus, more studies on the development of unisensory abilities are needed to advance our understanding with regards to the development of MSI skills in ASD. If alterations exist in the processing of basic sensory inputs, we would expect difficulties at the later integration stage. Now, if the development of these processing skills is disrupted, we might expect even more atypicalities at the integration stage.

The current view on the development of multisensory processing skills argues against an all-or-none dichotomy between integration and differentiation views of perceptual development (Lickliter & Bahrick, 2004). In line with this, some current theories on synaesthesia, argue that this phenomenon might be due to the fact that the senses are not as differentiated as initially thought (Maurer, 1993). Similarly, we may have to consider that either differentiation or integration processes might not unfold adequately in the perceptual development of autism, leading to alterations in the processing of unisensory and multisensory information.

7.4. Alterations in Attentional Processing in ASD

Attention mechanisms are amongst the most studied functions in ASD and attention deficits are one of the most frequent comorbidities observed in this population. The literature shows that autistic individuals present with difficulties in selective and spatial attention, including deficits in the disengagement and shifting of attention, whereas abilities of sustained attention are generally preserved. Recent research has shown that MOT skills involve multifocal attention, which is the capacity to allocate attention to multiple areas at the same time (Cavanagh & Alvarez, 2005). Whereas this capacity was found to be decreased in our sample of autistic adults, our study also showed that autistics' performance was significantly reduced in speed compared to that of typical controls when asked to track a single object, and thus to allocate their attention to one moving object in a set of distracters. It therefore seems that it is not the capacity to allocate attention to multiple areas *per se* that was found to be impaired in autistic participants, but rather the velocity, at which they were able to track one or more objects, that was affected, showing that they were less able to rapidly allocate their attention to one or more dynamic events.

This is further corroborated by findings of an overly broad focus in autism (Burack, 1994). As previously described, autistic participants' performance improved in the presence of an exogenously imposed focus when no distracters were present, while performance did not improve in the presence of the window, when distracters were present. Thus, the autistic participant's inability to focus attention optimally was aided by the prosthethic focus, however this improvement was negated by the distracter stimuli. Given that in both our conditions, participants were required to track spheres in a set of distracters, an overly broad focus may have similarly impacted their performance on both these conditions, as it may have hindered participants from maintaining tracking objects in focus, resulting in their inability to track objects as rapidly as controls. The capacity to focus on the fixation point and to simultaneously follow one or multiple objects amongst a set of distracters being inherent to a good performance on the MOT task, our findings therefore reflect ASD participants diminished ability on this task and hence extend previous findings of an overly broad focus.

Finally, similarly as attention functions may influence sensory perception, for instance through the active versus passive attending to a sensory stimuli, sensory symptoms may influence performance as well, and we therefore have to pay attention to the interaction between these processes when considering our results.

7.5. Sensory and Attentional Processing as Primary Alterations in ASD

As we know, autism is diagnosed based on behavioural observation. However, underlying mechanisms for the atypical behavioural presentation observed in ASD remain unclear. All that we know to date is that autistic individuals present with negative symptoms, including difficulties in social interaction and communication, as well as positive symptoms such as repetitive and stereotyped behaviours. Various theories have emerged in an overall effort to understand the origins of these behaviours, of which many concluded to some type of alteration in sensory processing, of either positive ("enhanced") or negative ("weak") nature.

Our findings are in line with these previous findings, in that we also found abnormalities in sensory processing. At the same time, we like to extend these conclusions by merging observations in sensory processing with observations in attentional functions, as we believe these to be invariably related amongst each other. In our daily life, sensory perception is highly dependent on attentional focus. At the same time, attention is greatly influenced by sensory perception. Very simplified, we can say that energy flows where attention goes, in the sense that we pay attention to what attracts our attention. However, what attracts our attention is what stimulates our senses. As our focus turns to the input of our senses, we may become more aware of information coming through a certain sense. As a sensory input becomes stronger, it necessarily attracts our attention due to its intensity. These intensity levels evidently vary from one individual to another. What remains is that our sensory and attentional functions are involuntarily linked to one another.

The previous sections showed that attention could impact how we interpret our results in sensory processing, as we have to consider the allocation of attention to the stimuli to be processed. At the same time, we saw that sensory symptoms can influence performance. Previous authors have argued that differences in findings between tasks could be explained by the active attending to the stimuli. This is consistent with evidence from an auditory mismatch negativity study, showing that impaired automatic processing could be normalized through the investment of attention (Dunn, Gomes, & Gravel, 2008). We also find an increased interest in the role of attention in multisensory processing in the recent literature (e.g., Talsma, Doty, & Woldorff, 2007; Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010). Others suggest links between attention issues and adaptive behaviours in autism. For instance, observations of heightened reactivity to seemingly meaningless stimuli (e.g., intense tantrums to the hum of a blender) may be related to a neurobehavioral driven distractibility (Allen & Courchesne, 2001) and narrowed interests and repetitive behaviours are suggested to represent deficits in attentional shifting (Marco et al., 2011). Some authors offer evidence from reports of sensory sensitivities (e.g., touch, taste, smell), proposing that these may be due to an overly broad focus and difficulty filtering out perceptual information (Wiggins et al., 2009). Hence, as alterations in basic sensory processing may lead to adaptive behaviours, so may issues in attentional processing. This is well summarized by Blackburn (1999, p. 7): "Sensory issues and attentional issues are most likely both real and both primary; in some case one may help cause the other".

It appears then that both sensory processing and attentional functions indeed play an important role as primary functions, which when impaired may influence later development of higher level functions, such as social interaction, and communication. For instance, following a conversation does not only imply the tracking of multiple nonverbal cues at the same time (multiple events), it also involves the processing of MSI (integration of audiovisual inputs). A deficit in one or the other of these abilities evidently will impact our ability to follow the conversation, which may be interpreted as a social deficit, but in itself is not the primary deficit. Thus, observed behaviours are evidently influenced in many different ways that we may not even be aware of at this stage of our knowledge. However, these functions seem to be building blocks, which are altered from young age on, as seen in our developmental study, and do not mature over time. While we only measured these two functions separately, it would be important in future studies to measure the interaction of the two and their mutual influence on each other.

To date, the diagnosis of autism is still based on measuring behavioural output. Anticipated changes in diagnostic criteria certainly present a first step in the right direction by including an item on sensory reactions, even though this item is still a measure of adaptive behaviour that may result from anomalies in sensory processing or attention issues. Obviously, autism is a multifaceted condition, hence the notion of a spectrum disorder, and we are only at the beginning stages of putting the pieces together. Other factors may play a role in the clinical presentation of the disorder, however in order to further our understanding, it remains crucial to consider the integrity of primary functions in the evaluation of behavioural output.

7.6. Relationship to Anomalies in the Brain

A wide variety of studies report anomalies in brain structure and functional connectivity in ASD. Many brain regions have been implicated in the processing, modulating and integration of sensory information. A particular focus was given to the superior colliculus, the cerebellum, and the frontal lobes in making sense of the rapid stream of information, being mediated by attentional demands and resources (Stein & Meredith, 1990). Theories of disordered connectivity suggest implications for the integration of information from the different relay stations within a functional network, leading to dysfunctional patterns of brain connectivity and as a result to deficits in the integration of multisensory cues (Brandwein et al., 2012).

Considering that we cannot precisely say which structures are involved in the completion of our tasks, we can only draw tentative comparisons between previously found anomalies in the neuroanatomy of ASD and brain regions potentially involved in the completion of our tasks. However, what we can say is that both our studies required processing involving large networks, and this seems to be in line with previous findings. Research in multisensory processing showed that behavioral deficits were paralleled by less effective neural integration, with individuals with ASD relying on different cortical networks during an early multisensory processing stage (Brandwein et al., 2012). Anomalies found in the thalamus (e.g., Tsatsanis, 2003; Waiter, 2005) and corpus callosum may have had repercussions on the interhemispheric transfer involved in our multisensory task. Additionally, the amygdaloid complex, amongst others a multisensory convergence zone (Calvert, 2001), is a region well known to be impaired in autism (Baumann & Kemper, 1994). Further anatomical evidence has pointed to abnormalities in long-range connections (Barnea-Goraly et al., 2004), and to alterations in the cerebellum (Bailey et al., 1998; Courchesne, 1997), with developmental cerebellar abnormality possibly contributing to the attentional impairments seen in autism (Courchesne, 1987). Studies investigating MOT processing in the brain, although investigating 2D-MOT, have found the parietal cortex to be involved (Culham et al., 2001; Jovicich et al., 2001), which is also a region that may be associated with cross-modal processing in the human brain (Calvert & Thesen, 2004), and has been found to show anatomical abnormalities in a substantial proportion of autistic individuals (Courchesne, Press, & Yeung-Courchesne, 1993). Decreased concentration was found in gray and white matter in the cerebral cortex and the cerebellum and to develop less over time in autistic children (Courchesne et al., 2001). This finding is highly interesting with regards to developmental findings that we obtained on our first study, in which we did not observe any maturation effects in our autism sample. Given the roles of both gray and white matter, the first being primarily associated with processing and cognition, and the second acting as a relay and coordinating communication between different brain regions (Fields, 2008), we can imagine how this may impact the development if anomalies are found here.

As previously mentioned, we cannot really know which cortical or sub-cortical structures were involved in our tasks. Furthermore, as research has shown, a modular approach to brain-behaviour relationships in autism may only be mildly fruitful. Notwithstanding this, it still seems evident that similar brain regions involved in the processing of multisensory information and attentional functions are found to be anomalous in autism.

7.7. Clinical Implications

As discussed previously, anomalies in sensory processing and attentional functions can have repercussions at the behavioural level. Both our studies were specifically designed to have an ecological character, therefore facilitating the application of findings to the everyday reality of individuals with ASD. Research proposed that difficulties with integration of multiple sensory modalities might lead to different types of adaptive behaviours (Cascio et al., 2008), reflected in either positive symptoms such as repetitive behaviours or negative symptoms such as withdrawal from social situations because of overstimulation (Grandin, 2000). Evidence suggested that sensory processing abnormalities are more common during infancy and childhood than during adulthood (Baranek, Foster, Berkson, 1997a) and were found to be correlated with severity of autism in children, but not in adolescents and adults (Kern et al., 2007), as well as with higher levels of stereotypic and repetitive behaviours (Baranek, Foster, & Berkson, 1997b).

The findings from the present studies may help bring more clarity to some accounts of adaptive behaviours. Findings from our MOT study may have implications with regards to the everyday life of an autistic person. Be it in a crowded school environment or while taking public transportation, we are constantly exposed to multiple events happening at the same time. The fact that autistic adults were less able to allocate their attention as rapidly as typical individuals to one or more dynamic events may impact their ability to use public transport for travel or navigate within crowded places such as for example in a shopping mall. This obviously has implications for their life, as well as the life of persons surrounding them. At the same time, our finding that autistic children were less able to integrate visuo-tactile information can have an impact on how these children relate with objects in their environment, as size perception is one amongst other prerequisites for object recognition. Further, as we studied the active sense of touch, in a much larger sense, this may apply to how these children interact with other persons, for instance in the exchange of gestures between persons.

7.8. Methodological Considerations

When we decide to study a clinical population that by definition classifies as a spectrum disorder, we are automatically faced with a number of methodological considerations with regards to the selection of our samples. As previously discussed, our current understanding of autism as a spectrum disorder accounts for the variability in symptom severity and intellectual functioning, as well as the overall heterogeneity in task performance and symptom expression commonly observed in the ASD population. Individuals with ASD are remarkably varied in their intellectual abilities and current estimates suggest that, whereas approximately half of all individuals with ASD are mildly to profoundly cognitively impaired, half have cognitive abilities within the normal range of intelligence, and a substantial minority have IQs well above normal (Joseph, 2011). In addition, individuals with autism frequently present with an unusual degree of unevenness in their cognitive abilities and a Wechsler IQ profile with Verbal IQ (VIQ) lower than PIQ has often been associated with autism (Happé, 1994; Lincoln, Allen, & Kilman, 1995; Lincoln). Whereas recent studies have questioned this prototypical Wechsler VIQ-PIQ profile in autism among higher-ability individuals (Williams, Goldstein, Kojkowski, & Minshew, 2008), they have also concluded that IQ discrepancies, particularly those favouring PIQ over VIQ, may be more frequent at lower levels of cognitive ability (Rumsey, 1992).

In light of this evidence, our choice for matching our two ASD samples was twofold. First, it was recruitment-related in that we recruited ASD children and adolescents for our first study from a specialized school for children with ASD. Given that we did not find a correlation between performance on our task and IQ or any subscale of IQ, we opted to match the sample of our first study on PIQ, in order to be able to also include students with lower levels of cognitive ability. On the contrary, we were able to recruit ASD participants for our second study from a specialized clinic for autistic persons. Because the adults who participated in this study all had a FSIQ within the average range, we chose to match our sample on the FSIQ. Secondly, we took task difficulty into consideration when making the decision with regards to the matching of our samples. Given that the nature of the task in our first study was entirely non-verbal and only required subjects to make a judgment on the size of two stimuli, participants' VIQ did not appear to be relevant. However, because the second task involved high-level cognitive demands and required a certain level of verbal abilities to understand oral instructions, it appeared appropriate to take into consideration their VIQ.

Given that participants with ASD and TD performed IQ tests in both our studies and that these tests involve some form of unisensory and multisensory integration and attentional processing, it appears important to consider factors that led participants with ASD and TD to perform similarly at those IQ (sub)tests, but to significantly differ at the experimental unisensory and multisensory integration and attention tasks that we used in our studies. As for our first study, we looked at size perception, which is a fundamental aspect of form perception and hence constitutes a prerequisite for higher order processes such as object recognition. We focused on the relationship between the physical properties of our stimuli and the perceptual responses to these stimuli by our participants. Thus, using a psychophysical level of analysis, we were able to directly measure perception and to observe significant impairments at the input stage, whereas these differences were not observed at the output stage of behaviour, as measured by the IQ test. On the contrary to the tasks employed in our studies, the inherent nature of IQ tests does not require participants to process information at the threshold level. While some of the Wechsler subtests certainly do involve the measure of perceptual functioning (e.g., Block Design, Matrix Reasoning), this measure is not at the level of physical properties of the stimuli, although we may at times observe behaviour indicative of an ASD participant examining the physical parameters of the test material (e.g., the blocs) without this influencing the test performance per se. Whereas a participant may be required to match patterns to reconstruct an image, this process involves higher cognitive processes than if the person was required to distinguish between the size of two coins at a low level of perception. Our second study was a perceptual-cognitive task linking low-level attentional processing with high-level cognitive demands and our results were equally obtained at the threshold level. Furthermore, whereas standard IQ tests do involve components measuring processing speed, these subtests or any other measures on the IQ tests do not involve any type of dynamic visual processing. Thus, while we would expect autistic participants' impairments to impact their daily functioning when required to attend to dynamic events and maintain their focus in the face of moving distracters, it is not surprising that we did not find these significant differences on our measures of IQ.

All this being said, by gaining a better understanding of these underlying sensory and attentional processes, we will also be able to inform the development of more appropriate tests to measure cognitive functioning in clinical populations such as ASD in the future. This is of special relevance in light of the fact that there exists an important literature in autism research dedicated solely to the matching of ASD participants.

7.9. Future Directions

A series of future directions is possible following our studies, of which several are elaborated here for discussion purposes.

7.9.1. Developmental Aspects

For the Cross-modal Size Discrimination Task, it would be interesting to do a longitudinal follow-up of the same participants, for instance after a period of one or two years, in order to compare if the results obtained through a cross-sectional approach were maintained within subjects. At the same time, it would be equally important to study the development of MOT capacities over time and throughout development, in order to see how these abilities would develop as a function of age in typical development and thereafter in atypical development. Given findings from previous studies showing impairments in the development of biological motion processing in autistic children (Annaz et al., 2010), in combination with results from our first study, we would not be surprised to find alterations in the development of MOT abilities in a sample of autistic children.

7.9.2. Potential for Training

While considering how MOT abilities might develop as a function of development, it would be similarly important to consider how they may develop, and even improve, as a function of training in autism. Previous research has shown the potential of MOT in the training of perceptual-cognitive skills in high-level athletes (Faubert & Sidebottom, 2012). Considering that we found a deficit in MOT capacities in autistic adults, it would be worthwhile, as proposed in our second article, to investigate if these abilities are plastic and if training on the MOT task is something autistic individuals could equally benefit from. Thus, following the previous suggestion to study the development of MOT capacities throughout development, and given that it is very likely that the brain is more plastic in younger than older individuals, this hypothesis could be tested simultaneously in typical and atypical development. Two studies could be run alongside, one testing the development of these abilities over time in typical and atypical development and the second investigating the effects of training and plasticity in ASD and TD children while controlling for maturational effects. In this second study, we could test the performance of two groups of ASD children, one group receiving MOT training and the other group not receiving MOT training (or receiving some sort of placebo training to control for factors related to the reception of an intervention per se). We could then compare the performance of both groups before and after training to evaluate the effects of training and plasticity.

Previous studies in speech perception showed that training in unisensory conditions could improve performance on multisensory abilities in ASD, hence demonstrating the transfer of skills across modalities. Thus, coming back to the idea of developmental cascades, if autistic children could be helped to "catch up" through specific training, at least on certain abilities, this might help further their development in other domains, as for example in social functioning. Although we found a general developmental deficit on our task in ASD and not a delay in these abilities, we do not know whether this decrease in performance may improve with training. If children were able to benefit from training on higher-order tasks such as lip reading, we can expect them to benefit from training on much lower-level tasks such as discriminating the size of two coins. This should specifically hold true as premises of the well known and widely recognized behaviour therapy (Lovaas, 1987) are based on this same idea, to expose autistic children repeatedly to trials of simple information, in order to help them catch up with typical development.

7.9.5. Social and Multisensory Virtual Environments

Based on our own observations, we know that the virtual reality environment is a setting that autistic individuals highly appreciate being in. At the same time, it is a setting that allows for easy conception and manipulation of different variables, hence generating numerous possibilities for future research. These possibilities include, amongst others, the creation of social scenarios, in which the dynamic 3D-MOT task may be integrated within a social setting (e.g. in a shopping mall) to see how this might impact performance. Alternatively, visual cues of the 3D-MOT task could be combined with auditory cues, to evaluate if this may improve the performance of observers akin to the phenomenon of stochastic resonance, in which auditory noise facilitates visual sensations (Lugo, Doti, & Faubert, 2008). Other options include the creation of a gestalt within the tracking paradigm, in order to see if this may enhance or decrease results for autistic participants, although we would expect observers to perform less well. Finally, given previous evidence that showed that ASD participants benefitted from a prosthetic focus (Burack, 1994), it could be considered to integrate this in a standard MOT task, in order to continue to inform us about attentional limitations and possibilities in this population.

7.9.4. Potential for Screening

As a continuation to our first study, it would be worthwhile to study high-risk children (i.e. younger siblings of autistic children) to see if differences might already be observed at a much younger age, and with the general objective of identifying earlier fundamental skills, aiding in the detection of the disorder. The task may have to be adapted, so as to use a concept much simpler than size discrimination, however it would be interesting to continue developing this idea as a possible screening tool. This is true especially since sensory processing abnormalities have been found to manifest themselves very early in development, and therefore are thought to be among the most diagnostically relevant features of autism at an early age (O'Neill & Jones, 1997), which is now reflected in the changing diagnostic criteria. Finally, considering that current diagnostic instruments are highly dependent on culture and language, an overall effort is made in the research community to complement existing screening tools with more culture-independent instruments. Thus, in the long run, sensory screening tools definitely have the potential to aid in the cross-cultural study of autism, and research in this domain becomes increasingly prominent.

Conclusion

The present thesis examined visual and tactile unisensory and visuo-tactile multisensory processing, as well as the development of these abilities by use of a cross-modal size discrimination task in children with ASD, compared to children with TD. We further evaluated the capacities of autistic adults to allocate their attention to multiple areas at the same time, compared to typical adults, by means of a Multiple Object Tracking paradigm. The studies required participants either to integrate input from two sensory modalities at the same time, or to simultaneously attend to multiple events, and this within the same sensory system. We showed that autistic children were less able to process unisensory and multisensory information and that these abilities did not develop over time. Further, we found autistic adults to be less capable to track a single or multiple objects within a set of distracter, reflecting their diminished capacity to rapidly allocate attention to one or more dynamic events. Together, these findings reveal alterations with regards to the processing of multiple events at the same time, be it within one modality or across modalities, which may have important implications for the clinical presentation of this condition. If we consider sensory processing and attention to be primary functions that act as building blocks for further development, alterations at this level may lead to anomalies in the unfolding of higher-level functions such as social interaction and communication at a later stage.

Changes in the current diagnostic criteria reflect a shift in our understanding of the developmental disorder, with a general awareness emerging that autism is not only a spectrum disorder, but may also be a sensory processing disorder. The overall objective of this thesis was to emphasize the understanding of how basic sensory processing functions in autism and how individuals with ASD make use of this information in their everyday life. Anecdotal and empirical evidence will have to continue to inform one another, for it is autobiographical accounts and clinical reports of sensory and attentional symptoms that incite us to study these behaviours, and it is empirical evidence that helps us make sense of the clinical accounts. As pointed out in the section on future directions, there is tremendous potential for further exploration in both these areas of autism research. Given that both our studies have been the first of their kind in the field, there is certainly a need for more research to replicate and extend our findings, in the visuo-tactile domain in MSI processing, as well as in the field of Multiple Object Tracking. Finally, the autistic population being an incredibly fascinating and touching one to study, there is no doubt that we will continue to be challenged and surprised by its unique clinical presentation.

Bibliography

Allen, G., & Courchesne, E. (2001). Attention function and dysfunction in autism. *Front Biosci, 6*, D105-119.

Alvarez, G. A., & Cavanagh, P. (2005). Independent resources for attentional tracking in the left and right visual hemifields. *Psychol Sci, 16*(8), 637-643.

Amedi, A., Malach, R., Hendler, T., Peled, S., & Zohary, E. (2001). Visuo-haptic object-related activation in the ventral visual pathway. *Nat Neurosci, 4*(3), 324-330.

American Psychiatric Association (2012). Retrieved from www.dsm5.org/ProposedRevisions/Pages/proposedrevision.aspx?rid=94

American Psychiatric Association (2000). *Diagnostic and statistical manual of mental disorders* (4th ed., text rev.). Washington, DC: American Psychiatric Association.

American Psychiatric Association (1980). *Diagnostic and statistical manual of mental disorders* (3rd ed.). Washington, DC: American Psychiatric Association.

Annaz, D., Remington, A., Milne, E., Coleman, M., Campbell, R., Thomas, M. S., et al. (2010). Development of motion processing in children with autism. *Dev Sci, 13*(6), 826-838.

Bahrick, L. E., & Lickliter, R. (2000). Intersensory redundancy guides attentional selectivity and perceptual learning in infancy. *Dev Psychol, 36*(2), 190-201.

Bahrick, L. E., & Todd, J. T. (2012). Multisensory processing in autism spectrum disorders: Intersensory processing disturbance as a basis for atypical development. In B. E. Stein (Ed.), *The new handbook of multisensory processes* (pp. 657-674). Cambridge, MA: MIT Press.

Bailey, A., Luthert, P., Dean, A., Harding, B., Janota, I., Montgomery, M., et al. (1998). A clinicopathological study of autism. *Brain, 121(5)*, 889-905.

Baker, A. E., Lane, A., Angley, M. T., & Young, R. L. (2008). The relationship between sensory processing patterns and behavioural responsiveness in autistic disorder: a pilot study. *J Autism Dev Disord, 38*(5), 867-875.

Banati, R. B., Goerres, G. W., Tjoa, C., Aggleton, J. P., & Grasby, P. (2000). The functional anatomy of visual-tactile integration in man: a study using positron emission tomography. *Neuropsychologia, 38*(2), 115-124.

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

Baranek, G. T., Foster, L. G., & Berkson, G. (1997a). Sensory defensiveness in persons with developmental disabilities. *Occup Ther J Res, 17*, 173-185.

Baranek, G. T., Foster, L. G., & Berkson, G. (1997b). Tactile defensiveness and stereotyped behaviors. *Am J Occup Ther, 51*(2), 91-95.

Barnea-Goraly, N., Kwon, H., Menon, V., Eliez, S., Lotspeich, L., & Reiss, A. L. (2004). White matter structure in autism: preliminary evidence from diffusion tensor imaging. *Biol Psychiatry, 55*(3), 323-326.

Baron-Cohen, S., & Belmonte, M. K. (2005). Autism: a window onto the development of the social and the analytic brain. *Annu Rev Neurosci, 28*, 109-126.

Bauman, M. L., & Kemper, T. L. (1994). Neuroanatomic observations of the brain in autism. In M. L. Bauman & T. L. Kemper (Eds.), *The Neurobiology of Autism* (pp. 119-145). Baltimore, MD: The Johns Hopkins University Press.

Bebko, J. M., Weiss, J. A., Demark, J. L., & Gomez, P. (2006). Discrimination of temporal synchrony in intermodal events by children with autism and children with developmental disabilities without autism. *J Child Psychol Psychiatry, 47*(1), 88-98.

Bergman, P., & Escalona, S. K. (1949). Unusual sensitivities in very young children. *Psychoanal Stud Chil, 3*(4), 333-352.

Behrmann, M., Thomas, C., & Humphreys, K. (2006). Seeing it differently: visual processing in autism. *Trends Cogn Sci, 10*(6), 258-264.

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

Birch, H. G., & Lefford, A. (1963). Intersensory development in children. *Monogr Soc Res Child Dev, 28*, 1-47.

Blackburn, J. (1999). My Inside View of Autism. Retrieved from www.planetc.com/urers/blackjar/aisub (site no longer active).

Blakemore, S. J., Tavassoli, T., Calo, S., Thomas, R. M., Catmur, C., Frith, U., et al. (2006). Tactile sensitivity in Asperger syndrome. *Brain Cogn, 61*(1), 5-13.

Bogdashina, O. (2003). *Sensory perceptual issues in autism and Asperger Syndrome: Different sensory experiences - Different perceptual worlds*. London, Uk: Jessica Kingsley.

Bonneh, Y. S., Belmonte, M. K., Pei, F., Iversen, P. E., Kenet, T., Akshoomoff, N., et al. (2008). Cross-modal extinction in a boy with severely autistic behaviour and high verbal intelligence. *Cogn Neuropsychol, 25*(5), 635-652.

Bower, T. G. R. (1974). *Development in infancy*. San Francisco, CA: Freeman.

Brandwein, A. B., Foxe, J. J., Butler, J. S., Russo, N. N., Altschuler, T. S., Gomes, H. & Molholm, S. (2012). The development of multisensory integration in high-functioning autism: high-density electrical mapping and psychophysical measures reveal impairments in the processing of audiovisual inputs. *Cerebral Cortex*. 2012 May 24. [Epub ahead of print].

Brock, J., Brown, C. C., Boucher, J., & Rippon, G. (2002). The temporal binding deficit hypothesis of autism. *Dev Psychopathol, 14*(2), 209-224.

Burack, J. A. (1994). Selective attention deficits in persons with autism: preliminary evidence of an inefficient attentional lens. *J Abnorm Psychol, 103*(3), 535-543.

Bushnell, E. W. (1994). A dual-processing approach to cross-modal matching: Implications for development. In D. J. Lewkowicz & R. Lickliter (Eds.), *The development of intersensory perception: Comparative perspectives* (pp. 19-38). Hillsdale, NJ: Erlbaum.

Buxhoeveden, D. P., Semendeferi, K., Buckwalter, J., Schenker, N., Switzer, R., & Courchesne, E. (2006). Reduced minicolumns in the frontal cortex of patients with autism. *Neuropathol Appl Neurobiol, 32*(5), 483-491.

Calvert, G. A. (2001). Crossmodal processing in the human brain: insights from functional neuroimaging studies. *Cereb Cortex, 11*(12), 1110-1123.

Calvert, G. A., & Thesen, T. (2004). Multisensory integration: methodological approaches and emerging principles in the human brain. *J Physiol Paris, 98*(1-3), 191-205.

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

Cascio, C., McGlone, F., Folger, S., Tannan, V., Baranek, G., Pelphrey, K. A., et al. (2008). Tactile perception in adults with autism: a multidimensional psychophysical study. *J Autism Dev Disord, 38*(1), 127-137.

Casey, B. J., Gordon, C. T., Mannheim, G. B., & Rumsey, J. M. (1993). Dysfunctional attention in autistic savants. *J Clin Exp Neuropsychol, 15*(6), 933-946.

Cavanagh, P., & Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. *Trends Cogn Sci, 9*(7), 349-354.

Cesaroni, L., & Garber, M. (1991). Exploring the experience of autism through firsthand accounts. *J Autism Dev Disord, 21*(3), 303-313.

Chawarska, K., Volkmar, F., & Klin, A. (2010). Limited attentional bias for faces in toddlers with autism spectrum disorders. *Arch Gen Psychiatry, 67*(2), 178-185.

Courchesne, E. (1997). Brainstem, cerebellar and limbic neuroanatomical abnormalities in autism. *Curr Opin Neurobiol, 7*(2), 269-278.

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

Courchesne, E., Redcay, E., Morgan, J. T., & Kennedy, D. P. (2005). Autism at the beginning: microstructural and growth abnormalities underlying the cognitive and behavioral phenotype of autism. *Dev Psychopathol, 17*(3), 577-597.

Courchesne, E., Townsend, J., Akshoomoff, N. A., Saitoh, O., Yeung-Courchesne, R., Lincoln, A. J., et al. (1994). Impairment in shifting attention in autistic and cerebellar patients. *Behav Neurosci, 108*(5), 848-865.

Culham, J. C., Brandt, S. A., Cavanagh, P., Kanwisher, N. G., Dale, A. M., & Tootell, R. B. (1998). Cortical fMRI activation produced by attentive tracking of moving targets. *J Neurophysiol, 80*, 2657-2670.

Dahlgren, S. O., & Gillberg, C. (1989). Symptoms in the first two years of life. A preliminary population study of infantile autism. *Eur Arch Psychiatry Neurol Sci, 238*(3), 169-174.

Dakin, S., & Frith, U. (2005). Vagaries of visual perception in autism. *Neuron, 48*(3), 497-507.

David, N., Schneider, T. R., Vogeley, K., & Engel, A. K. (2011). Impairments in multisensory processing are not universal to the autism spectrum: No evidence for cross-modal priming deficits in Asperger syndrome. *Autism Res, 4*, 383-388.

Delacato, C. H. (1974). *The Ultimate Stranger: The Autistic Child*. Belford, Uk: Ann Arbor Publishers.

de Gelder, B., Vroomen, J., & van der Heide, L. (1991). Face recognition and lip-reading in autism. *Eur J Cogn Psychol 3*, 69-86.

DeMeyer, M. K. (1976). Motor, perceptual-motor and intellectual disabilities of autistic children. In L. Wing (Ed.), *Early childhood autism* (pp. 169-193). Oxford, UK: Pergamon.

Dunn, M., Gomes, H., & Gravel, J. (2008). Mismatch negativity in children with autism and typical development. *J Autism Dev Disord, 38*, 52-71.

Dunn, W. (2001). The sensations of everyday life: empirical, theoretical, and pragmatic considerations. *Am J Occup Ther, 55*(6), 608-620.

Dunn, W. (2007). *Living Sensationally: Understanding Your Senses*. London, UK: Jessica Kingsley.

Dunn, W., Myles, B. S., & Orr, S. (2002). Sensory processing issues associated with Asperger syndrome: a preliminary investigation. *Am J Occup Ther, 56*(1), 97-102.

Ellemberg, D., Lewis, T. L., Meghji, K. S., Maurer, D., Guillemot, J. P., & Lepore, F. (2003). Comparison of sensitivity to first- and second-order local motion in 5-year-olds and adults. *Spat Vis, 16*(5), 419-428.

Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature, 415*(6870), 429-433.

Ernst, M. O., & Bulthoff, H. H. (2004). Merging the senses into a robust percept. *Trends Cogn Sci, 8*(4), 162-169.

Faubert, J., & Sidebottom, L. (2012). The Neurotracker System: Its role for perceptual-cognitive training of athletes and its potential impact on injury reductions and concussion management in sports. *J Clin Sport Psychol, 6*, 85-102.

Fein, D., Tinder, P., & Waterhouse, L. (1979). Stimulus generalization in autistic and normal children. *J Child Psychol Psychiatry, 20*(4), 325-335.

Fields, D. (2008). "White Matter". *Scientific American, 298*(3), 54-61.

Fombonne, E., Zakarian, R., Bennett, A., Meng, L., & McLean-Heywood, D. (2006). Pervasive developmental disorders in Montreal, Quebec, Canada: prevalence and links with immunizations. *Pediatrics, 118*(1), e139-150.

Fougnie, D., & Marois, R. (2006). Distinct capacity limits for attention and working memory: Evidence from attentive tracking and visual working memory paradigms. *Psychol Sci, 17*(6), 526-534.

Freides, D. (1974). Human information processing and sensory modality: cross-modal functions, information complexity, memory, and deficit. *Psychol Bull, 81*(5), 284-310.

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

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

Garretson, H. B., Fein, D., & Waterhouse, L. (1990). Sustained attention in children with autism. *J Autism Dev Disord, 20*(1), 101-114.

Gibson, E. J. (1969). *Principles of perceptual learning and development* Englewood Cliffs, NJ: Prentice Hall.

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

Gottfried, A. W., Rose, S. A., & Bridger, W. H. (1977). Cross-modal transfer in human infants. *Child Dev, 48*(1), 118-123.

Grandin, T. (1992). An inside view of autism. In Schopler & Mesibov (Eds.), *High-functioning individuals with autism* (pp. 105-126). New York, NY: Plenum Press.

Grandin, T. (1996). *Thinking in pictures and other reports from my life with autism.* New York, NY: Doubleday.

Grandin, T. (2008). *The way I see it. A personal look at autism and Asperger's*. Arlington, TX: Future Horizons.

Grandin, T., & Scariano, M. (1986). *Emergence: Labelled autistic*. Novato, CA: Arena.

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

Grossenbacher, P. G., & Lovelace, C. T. (2001). Mechanisms of synesthesia: cognitive and physiological constraints. *Trends Cogn Sci, 5*(1), 36-41.

Hall, G. B., Szechtman, H., & Nahmias, C. (2003). Enhanced salience and emotion recognition in Autism: a PET study. *Am J Psychiatry, 160*(8), 1439-1441.

Happé, F. G. (1994). Wechsler IQ profile and theory of mind in autism: a research note. *J Child Psychol Psychiatry, 35*(8), 1461-1471.

Happé, F. (2005). The weak central coherence account of autism In Volkmar, Paul, Klin & Cohen (Eds.), *Handbook of autism and pervasive developmental disorders, Vol. 1: Diagnosis, development, neurobiology, and behavior* (3rd ed., pp. 640-649). New York, NY: John Wiley & Sons.

Happé, F., & Frith, U. (2006). The weak coherence account: detail-focused cognitive style in autism spectrum disorders. *J Autism Dev Disord, 36*(1), 5-25.

Harrison, J., & Hare, D. J. (2004). Brief report: assessment of sensory abnormalities in people with autistic spectrum disorders. *J Autism Dev Disord, 34*(6), 727-730.

Helbig, H. B., & Ernst, M. O. (2007). Optimal integration of shape information from vision and touch. *Exp Brain Res, 179*(4), 595-606.

Herbert, M. R. (2011). The Neuroanatomy of ASD. In D. Fein (Ed.), *The Neuropsychology of Autism* (pp. 47-76). New York, NY: Oxford University Press.

Herbert, M., & Anderson (2008). An expanding spectrum of autism models: From fixed developmental defects to reversible functional impairments. In A. Zimmerman (Ed.), *Autism: Current Theories and Evidence* (pp. 429-463). New York, NY: Humana Press.

Hermelin, B., & O'Connor, N. (1970). *Psychological experiments with autistic children*. Oxford, UK: Pergamon 142.

Hershberger, W. A., & Misceo, G. F. (1996). Touch dominates haptic estimates of discordant visual-haptic size. *Percept Psychophys, 58*(7), 1124-1132.

Howard, I. P., & Templeton, W. B. (1966). *Human Spatial Orientation*. London, UK: Wiley.

Hus, V., Pickles, A., Cook, E. H., Jr., Risi, S., & Lord, C. (2007). Using the autism diagnostic interview–revised to increase phenotypic homogeneity in genetic studies of autism. *Biol Psychiatry, 61*(4), 438-448.

Hutt, C., Hutt, S. J., Lee, D., & Ounsted, C. (1964). Arousal and Childhood Autism. *Nature, 204*, 908-909.

Iarocci, G., & McDonald, J. (2006). Sensory integration and the perceptual experience of persons with autism. *J Autism Dev Disord, 36*(1), 77-90.

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

Jones, R. S. P., Quigney, C., & Huws, J. C. (2003). First-hand accounts of sensory perceptual experiences in autism: A qualitative analysis. *J Intellect Dev Dis, 28*(2), 112-121.

Joseph, R. M. (2011).The Significance of IQ and Differential Cognitive Abilities for Understanding ASD. In D. Fein (Ed.), *The Neuropsychology of Autism* (pp. 281-294). New York, NY: Oxford University Press.

Jovicich, J., Peters, R. J., Koch, C., Braun, J., Chang, L., & Ernst, T. (2001). Brain Areas Specific for Attentional Load in a Motion-Tracking Task. *J Cognitive Neurosci 13*(8), 1048-1058.

Just, M. A., Cherkassky, V. L., Keller, T. A., & Minshew, N. J. (2004). Cortical activation and synchronization during sentence comprehension in high-functioning autism: evidence of underconnectivity. *Brain, 127*(Pt 8), 1811-1821.

Just, M. A., Cherkassky, V. L., Keller, T. A., Kana, R. K., & Minshew, N. J. (2007). Functional and anatomical cortical underconnectivity in autism: evidence from an FMRI study of an executive function task and corpus callosum morphometry. *Cereb Cortex, 17*(4), 951-961.

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

Kaye, K. L., & Bower, T. G. R. (1994). Learning and intermodal transfer of information in newborns. *Psychol Sci, 5*(5), 286-288.

Kenet, T. (2011). Sensory Functions in ASD. In D. Fein (Ed.), *The Neuropsychology of Autism* (pp. 215-224). New York, NY: Oxford University Press.

Kern, J. K., Trivedi, M. H., Garver, C. R., Grannemann, B. D., Andrews, A. A., Savla, J. S., et al. (2006). The pattern of sensory processing abnormalities in autism. *Autism, 10*(5), 480-494.

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

Kovacs, I., Kozma, P., Feher, A., & Benedek, G. (1999). Late maturation of visual spatial integration in humans. *Proc Natl Acad Sci U S A, 96*(21), 12204-12209.

Kuhl, P. K., & Meltzoff, A. N. (1982). The bimodal perception of speech in infancy. *Science, 218*(4577), 1138-1141.

Lewkowicz, D. J., & Lickliter, R. (1994). *The development of intersensory perception.* Hillsdale, NJ: Erlbaum

Lickliter, R., & Bahrick, L. E. (2004). Perceptual development and the origins of multisensory responsiveness. In Calvert, Spence & Stein (Eds.), *The handbook of multisensory processes* (pp. 3-25). Cambridge, MA: MIT Press.

Lincoln, A. J., Allen, M., Kilman, A. (1995). The assessment and interpretation of intellectual abilities in people with autism. In E. Schopler & G. Mesibov (Eds.), *Learning and cognition in autism* (pp. 89-117). New York: Plenum Press.

Lovaas, O. I. (1987). Behavioral treatment and normal educational and intellectual functioning in young autistic children. *J Consult Clin Psychol, 55*(1), 3-9.

Lovaas, O. I., & Schreibman, L. (1971). Stimulus overselectivity of autistic children in a two stimulus situation. *Behav Res Ther, 9*(4), 305-310.

Lovaas, O. I., Schreibman, L., Koegel, R., & Rehm, R. (1971). Selective responding by autistic children to multiple sensory input. *J Abnorm Psychol, 77*(3), 211-222.

Lugo, E., Doti, R., & Faubert, J. (2008). Ubiquitous crossmodal Stochastic Resonance in humans: auditory noise facilitates tactile, visual and proprioceptive sensations. *PLoS ONE, 3*(8), e2860.

Mann, T. A., & Walker, P. (2003). Autism and a deficit in broadening the spread of visual attention. *J Child Psychol Psychiatry, 44*(2), 274-284.

Marco, E. J., Hinkley, L. B., Hill, S. S., & Nagarajan, S. S. (2011). Sensory processing in autism: a review of neurophysiologic findings. *Pediatr Res, 69*(5 Pt 2), 48R-54R.

Marks, L. E. (1978). *The unity of the senses: Interrelations among the modalities*. New York, NY: Academic Press.

Martineau, J., Roux, S., Adrien, J. L., Garreau, B., Barthelemy, C., & Lelord, G. (1992). Electrophysiological evidence of different abilities to form cross-modal associations in children with autistic behavior. *Electroencephalogr Clin Neurophysiol, 82*(1), 60-66.

Maurer, D. (1993). Neonatal synesthesia: Implications for the processing of speech and faces. In B. de Boysson-Bardies, S. de Schonen, P. W. Jusczyk, P. McNeilage

& J. Morton (Eds.), *Developmental neurocognition: Speech and face processing in the first year of life* (pp. 109-124). New York, NY: Kluwer Academic/Plenum Publishers.

McDonnell, P. M., & Duffett, J. (1972). Vision and touch: a reconsideration of conflict between the two senses. *Can J Psychol, 26*(2), 171-180.

McGurk, H., & MacDonald, J. (1976). Hearing lips and seeing voices. *Nature, 264*(5588), 746-748.

Meltzoff, A. N., & Borton, R. W. (1979). Intermodal matching by human neonates. *Nature, 282*(5737), 403-404.

Meltzoff, A. N., & Moore, M. K. (1977). Imitation of Facial and Manual Gestures by Human Neonates. *Science, 198*(4312), 75-78.

Meltzoff, A. N., & Moore, M. K. (1983). Newborn infants imitate adult facial gestures. *Child Dev, 54*(3), 702-709.

Miller, E. A. (1972). Interaction of vision and touch in conflict and nonconflict form perception tasks. *J Exp Psychol, 96*(1), 114-123.

Milne, E., Swettenham, J., Hansen, P., Campbell, R., Jeffries, H., & Plaisted, K. (2002). High motion coherence thresholds in children with autism. *J Child Psychol Psychiatry, 43*(2), 255-263.

Molholm, S., Ritter, W., Murray, M. M., Javitt, D. C., Schroeder, C. E., & Foxe, J. J. (2002). Multisensory auditory-visual interactions during early sensory processing in humans: a high-density electrical mapping study. *Brain Res Cogn Brain Res, 14*(1), 115-128.

Mongillo, E. A., Irwin, J. R., Whalen, D. H., Klaiman, C., Carter, A. S., & Schultz, R. T. (2008). Audiovisual processing in children with and without autism spectrum disorders. *J Autism Dev Disord, 38*(7), 1349-1358.

Moss, F., Ward, L. M., & Sannita, W. G. (2004). Stochastic resonance and sensory information processing: a tutorial and review of application. *Clin Neurophysiol, 115*(2), 267-281.

Mottron, L., Belleville, S., & Menard, E. (1999). Local bias in autistic subjects as evidenced by graphic tasks: perceptual hierarchization or working memory deficit? *J Child Psychol Psychiatry, 40*(5), 743-755.

Mottron, L., & Burack, J. (2001). Enhanced perceptual functioning in the development of autism. In Burack, Charman, Yirmiya & Zelazo (Eds.), *The development of autism: Perspectives from theory and research* (pp. 131-148). Mahwah, NJ: Erlbaum.

Mottron, L., Dawson, M., Soulières, I., Hubert, B., & Burack, J. (2006). Enhanced perceptual functioning in autism: an update, and eight principles of autistic perception. *J Autism Dev Disord, 36*(1), 27-43.

Mottron, L., Peretz, I., & Menard, E. (2000). Local and global processing of music in high-functioning persons with autism: beyond central coherence? *J Child Psychol Psychiatry, 41*(8), 1057-1065.

Muller, R. A. (2007). The study of autism as a distributed disorder. *Ment Retard Dev Disabil Res Rev, 13*(1), 85-95.

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

Muller, R. A., Shih, P., Keehn, B., Deyoe, J. R., Leyden, K. M., & Shukla, D. K. (2011). Underconnected, but how? A survey of functional connectivity MRI studies in autism spectrum disorders. *Cereb Cortex, 21*(10), 2233-2243.

Mundy, P., & Burnette, C. (2005). Joint attention and neurodevelopmental models of autism. In F. R. Volkmar, R. Paul, A. Klin & D. Cohen (Eds.), *Handbook of autism and pervasive developmental disorders, Vol. 1: Diagnosis, development, neurobiology, and behavior* Hoboken, NJ: John Wiley & Sons.

O'Hare, J. J. (1991). Perceptual integration. *J Wash Acad Sci, 81*, 44-59.

Oksama, L., & Hyönä, J. (2004). Is multiple object tracking carried out automatically by an early vision mechanism independent of higher-order cognition? An individual difference approach. *Visual Cognition, 11*(5), 631-671.

O'Neill, J. L. (1999). *Through the Eyes of Aliens: A book about autistic people.* London, Uk: Jessica Kingsley

O'Neill, M., & Jones, R. S. (1997). Sensory-perceptual abnormalities in autism: a case for more research? *J Autism Dev Disord, 27*(3), 283-293.

O'Riordan, M., & Passetti, F. (2006). Discrimination in autism within different sensory modalities. *J Autism Dev Disord, 36*(5), 665-675.

O'Riordan, M., & Plaisted, K. (2001). Enhanced discrimination in autism. *Q J Exp Psychol A, 54*(4), 961-979.

Ornitz, E. M., Guthrie, D., & Farley, A. H. (1977). The early development of autistic children. *J Autism Child Schizophr, 7*(3), 207-229.

Ornitz, E. M., & Ritvo, E. R. (1968). Perceptual inconstancy in early infantile autism. The syndrome of early infant autism and its variants including certain cases of childhood schizophrenia. *Arch Gen Psychiatry, 18*(1), 76-98.

Pashler, H. (1999). *The Psychology of Attention*. Cambridge, UK: Cambridge University Press.

Piaget, J. (1952). *The origins of intelligence*. New York, NY: Norton.

Perrott, D. R., Saberi, K., Brown, K., & Strybel, T. Z. (1990). Auditory psychomotor coordination and visual search performance. *Percept Psychophys, 48*(3), 214-226.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annu Rev Neurosci, 13*, 25-42.

Posner, M. I., Walker, J. A., Friedrich, F. J., & Rafal, R. D. (1984). Effects of parietal injury on covert orienting of attention. *J Neurosci, 4*(7), 1863-1874.

Power, R. P., & Graham, A. (1976). Dominance of touch by vision: generalization of the hypothesis to a tactually experienced population. *Perception, 5*(2), 161-166.

Pylyshyn, Z. (1994). Some primitive mechanisms of spatial attention. *Cognition, 50*(1-3), 363-384.

Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: evidence for a parallel tracking mechanism. *Spat Vis, 3*(3), 179-197.

Remington, A., Swettenham, J., Campbell, R., & Coleman, M. (2009). Selective attention and perceptual load in autism spectrum disorder. *Psychol Sci, 20*(11), 1388-1393.

Renner, P., Grofer Klinger, L., & Klinger, M. R. (2006). Exogenous and endogenous attention orienting in autism spectrum disorders. *Child Neuropsychol, 12*(4-5), 361-382.

Rentschler, I., Juttner, M., Osman, E., Muller, A., & Caelli, T. (2004). Development of configural 3D object recognition. *Behav Brain Res, 149*(1), 107-111.

Rice, S. A., Bigler, E. D., Cleavinger, H. B., Tate, D. F., Sayer, J., McMahon, W., et al. (2005). Macrocephaly, corpus callosum morphology, and autism. *J Child Neurol, 20*(1), 34-41.

Rimland, B. (1964). *Infantile autism*. New York, NY: Appleton-Century-Crofts.

Rippon, G., Brock, J., Brown, C., & Boucher, J. (2007). Disordered connectivity in the autistic brain: challenges for the "new psychophysiology". *Int J Psychophysiol, 63*(2), 164-172.

Rock, I., & Victor, J. (1964). Vision and Touch: An Experimentally Created Conflict between the Two Senses. *Science, 143*, 594-596.

Rogers, S. J. (2009). What are infant siblings teaching us about autism in infancy? *Autism Res, 2*, 125-137.

Rogers, S. J., & Ozonoff, S. (2005). Annotation: what do we know about sensory dysfunction in autism? A critical review of the empirical evidence. *J Child Psychol Psychiatry, 46*(12), 1255-1268.

Rose, S. A., Gottfried, A. W., & Bridger, W. H. (1981a). Cross-modal transfer in 6-month-old infants. *Dev Psychol, 17*(5), 661-669.

Rose, S. A., Gottfried, A. W., & Bridger, W. H. (1981b). Cross-modal transfer and information processing by the sense of touch in infancy. *Dev Psychol, 17*(1), 90-98.

Rose, S. A., Gottfried, A. W., & Bridger, W. H. (1983). Infants' cross-modal transfer from solid objects to their graphic representations. *Child Dev, 54*(3), 686-694.

Rosvold, H. E., Mirsky, A. F., Sarason, I., Bransome, E. D., Jr., & Beck, L. H. (1956). A continuous performance test of brain damage. *J Consult Psychol, 20*(5), 343-350.

Ruff, H. A., & Kohler, C. J. (1978). Tactual--visual transfer in six-month-old infants. *Infant Behav Dev, 1*, 259-264.

Russo, N., Foxe, J. J., Brandwein, A. B., Altschuler, T., Gomes, H., & Molholm, S. (2010). Multisensory processing in children with autism: high-density electrical mapping of auditory-somatosensory integration. *Autism Res, 3*(5), 253-267.

Rumsey, J. M. (1992). Neuropsychological studies of high-level autism. In E. Schopler & G. B. Mesibov (Eds.), *High-functioning individuals with autism* (pp. 41-64). New York: Plenum Press.

Schipul, S. E., Keller, T. A., & Just, M. A. (2011). Inter-regional brain communication and its disturbance in autism. *Front Syst Neurosci, 5*, 10.

Sekuler, R., Sekuler, A. B., & Lau, R. (1997). Sound alters visual motion perception. *Nature, 385*(6614), 308.

Shah, A., & Frith, U. (1983). An islet of ability in autistic children: a research note. *J Child Psychol Psychiatry, 24*(4), 613-620.

Shah, A., & Frith, U. (1993). Why do autistic individuals show superior performance on the block design task? *J Child Psychol Psychiatry, 34*(8), 1351-1364.

Shams, L., Kamitani, Y., & Shimojo, S. (2000). Illusions. What you see is what you hear. *Nature, 408*(6814), 788.

Shimojo, S., & Shams, L. (2001). Sensory modalities are not separate modalities: plasticity and interactions. *Curr Opin Neurobiol, 11*(4), 505-509.

Simmons, D. R., Robertson, A. E., McKay, L. S., Toal, E., McAleer, P., & Pollick, F. E. (2009). Vision in autism spectrum disorders. *Vision Res, 49*(22), 2705-2739.

Stein, B. E., & Meredith, M. A. (1990). Multisensory integration. Neural and behavioral solutions for dealing with stimuli from different sensory modalities. *Ann N Y Acad Sci, 608*, 51-65; discussion 65-70.

Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses*. Cambridge, MA: MIT Press.

Stein, B. E., Meredith, M. A., Huneycutt, W. S., & McDade, L. (1989). Behavioural indices of multisensory integration: orientation to visual cues is affected by auditory stimuli. *J Cogn Neurosci, 1*(12-24).

Streri, A. (1987). Tactile discrimination of shape and intermodal transfer in 2- to 3-month-old infants. *Brit J Dev Psychol, 5*(3), 213-220.

Streri, A. (2003). Cross-modal recognition of shape from hand to eyes in human newborns. *Somatosens Mot Res, 20*(1), 13-18.

Streri, A., & Gentaz, E. (2004). Cross-modal recognition of shape from hand to eyes and handedness in human newborns. *Neuropsychologia, 42*(10), 1365-1369.

Talsma, D., Doty, T. J., & Woldorff, M. G. (2007). Selective attention and audio-visual integration: is attending to both modalities a prerequisite for early integration? *Cereb Cortex, 17*, 679-690.

Talsma, D., Senkowski, D., Soto-Faraco, S., & Woldorff, M. G. (2010). The multifaceted interplay between attention and multisensory integration. *Trends Cogn Sci, 14*(9), 400-410.

Taylor, N., Isaac, C., & Milne, E. (2010). A comparison of the development of audiovisual integration in children with autism spectrum disorders and typically developing children. *J Autism Dev Disord, 40*(11), 1403-1411.

Tomchek, S. D., & Dunn, W. (2007). Sensory processing in children with and without autism: a comparative study using the short sensory profile. *Am J Occup Ther, 61*(2), 190-200.

Townsend, J., Courchesne, E., Covington, J., Westerfield, M., Harris, N. S., Lyden, P., et al. (1999). Spatial attention deficits in patients with acquired or developmental cerebellar abnormality. *J Neurosci, 19*(13), 5632-5643.

Townsend, J., Courchesne, E. and Egaas, B. (1996). Slowed orienting of covert visual-spatial attention in autism: Specific deficits associated with cerebellar and parietal abnormality. *Dev Psychopathol, 8*, 563-584.

Townsend, J., Harris, N. S., & Courchesne, E. (1996). Visual attention abnormalities in autism: delayed orienting to location. *J Int Neuropsychol Soc, 2*(6), 541-550.

Travers, B. G., Klinger, M. R., Klinger, L. G. (2011). Attention and Working Memory in ASD. In D. Fein (Ed.), *The Neuropsychology of Autism* (pp. 161-184). New York, NY: Oxford University Press.

Trick, L. M., Perl, T., & Sethi, N. (2005). Age-related differences in Multiple Object Tracking. *J Gerontol B Psychol Sci Soc Sci, 60*(2), P102-105.

Tsatsanis, K. D., Rourke, B. P., Klin, A., Volkmar, F. R., Cicchetti, D., & Schultz, R. T. (2003). Reduced thalamic volume in high-functioning individuals with autism. *Biol Psychiatry, 53*(2), 121-129.

van der Smagt, M. J., van Engeland, H., & Kemner, C. (2007). Brief Report: Can You See What is Not There? Low-level Auditory-visual Integration in Autism Spectrum Disorder. *J Autism Dev Disord, 37*(10), 2014-2019.

Volkmar, F. R., Cohen, D. J., & Paul, R. (1986). An evaluation of DSM-III criteria for infantile autism. *J Am Acad Child Psychiatry, 25*(2), 190-197.

Wainwright, J. A., & Bryson, S. E. (1996). Visual-spatial orienting in autism. *J Autism Dev Disord, 26*(4), 423-438.

Wainwright-Sharp, J. A., & Bryson, S. E. (1993). Visual orienting deficits in high-functioning people with autism. *J Autism Dev Disord, 23*(1), 1-13.

Waiter, G. D., Williams, J. H., Murray, A. D., Gilchrist, A., Perrett, D. I., & Whiten, A. (2005). Structural white matter deficits in high-functioning individuals with autistic spectrum disorder: a voxel-based investigation. *Neuroimage, 24*(2), 455-461.

Wass, S. (2011). Distortions and disconnections: disrupted brain connectivity in autism. *Brain Cogn, 75*(1), 18-28.

Waterhouse, L., Fein, D., & Modahl, C. (1996). Neurofunctional mechanisms in autism. *Psychol Rev, 103*(3), 457-489.

Williams, D. (1994). *Somebody somewhere*. London, UK: Doubleday.

Williams, D. L., Goldstein, G., Kojkowski, N., & Minshew, N. J. (2008). Do individuals with high functioning autism have the IQ profile associated with nonverbal learning disability? *Res Autism Spectr Disord, 2*(2), 353-361.

Wiggins, L. D., Robins, D. L., Bakeman, R., & Adamson, L. B. (2009). Brief report: sensory abnormalities as distinguishing symptoms of autism spectrum disorders in young children. *J Autism Dev Disord, 39*(7), 1087-1091.

Wing, L. (1969). The handicaps of autistic children - a comparative study. *J Child Psychol Psychiatry, 10*(1), 1-40.

Yantis, S. (1992). Multielement visual tracking: attention and perceptual organization. *Cogn Psychol, 24*(3), 295-340.

Zwaigenbaum, L., Bryson, S., Rogers, T., Roberts, W., Brian, J., & Szatmari, P. (2005). Behavioral manifestations in autism in the first year of life. *Int J Dev Neurosci, 23*, 143-152.