Université de Montréal

Auditory pitch perception in Autism Spectrum Disorder is associated with superior non-verbal abilities

Par
Rakhee Chowdhury

Département de psychologie
Faculté des arts et sciences

Mémoire présenté à la Faculté des études supérieures et postdoctorales
en vue de l'obtention du grade de Maître ès Sciences (M.Sc.)
En psychologie

Août 2016

Université de Montréal
Faculté des études supérieures et postdoctorales

Ce mémoire intitulé:

Auditory pitch perception in Autism Spectrum Disorder is associated with superior non-verbal abilities

Présenté par:
Rakhee Chowdhury

A été évalué par un jury composé des personnes suivantes:

Annie Bernier, présidente rapporteur
Alexandre Lehmann, membre du jury
Krista Hyde, directrice de recherche

Résumé

Le Trouble du Spectre Autistique (TSA) est souvent caractérisé par un profil auditif atypique et des atteintes au niveau du langage. Des études antérieures examinant la perception auditive simple et complexe dans les TSA et le développement typique présentent des conclusions mitigées quant à la nature des profils auditifs des deux groupes. De plus, des données contradictoires ont été rapportées en termes d'aptitudes cognitives chez les personnes atteintes de TSA. En conséquence, la relation qui existe entre la perception auditive et les habiletés verbales et non-verbales chez les TSA demeure mal comprise. En conséquence, cette étude cherche à mieux comprendre la relation entre le traitement du son et les aptitudes cognitives, en visant de comparer des enfants atteints de TSA à des enfants au développement typique. Dans la présente étude, les participants ont effectué une tâche auditive à bas-niveau et une tâche auditive mélodique à haut-niveau. Les capacités cognitives verbales et non-verbales ont été mesurées à l'aide des composantes du Wechsler Abbreviated Scale of Intelligence (WASI), un test de quotient intellectuel (QI). Les deux groupes ont obtenu des résultats similaires sur les deux tâches auditives ainsi que sur les mesures de QI. De plus, cette étude a démontré que les habiletés verbales ne permettent pas de prédire la performance sur la tâche auditive à bas-niveau ou sur la tâche auditive à haut-niveau dans les deux groupes. Cependant, les habiletés non-verbales semblent prédire une meilleure perception auditive sur les deux tâches auditives, et ce, pour les deux groupes. Ces résultats soulignent la présence d'habiletés auditives intactes dans un échantillon d'enfants atteints de TSA ayant un QI qui se situe dans la moyenne. De plus, l'étude actuelle met en évidence une relation entre la perception auditive et le raisonnement non-verbal, plutôt que le raisonnement verbal. Ainsi, les résultats de cette étude permettent d'approfondir la connaissance sur les différences individuelles qui existent dans la perception auditive auprès des personnes atteintes de TSA dans les contextes verbales et non-verbales, pour enfin contribuer à une meilleure caractérisation du phénotype du TSA.

Mots clé: autisme; pitch; auditif; cognitif; habiletés non-verbales; langage; développement typique

Abstract

Autism Spectrum Disorder (ASD) is often characterized by atypical sensory perception and cognitive profiles. However, previous studies have found mixed findings with regard to auditory processing in ASD. Discrepant findings have been reported in terms of cognitive abilities in ASD. Accordingly, auditory perception and its relation to verbal and non-verbal cognitive abilities in ASD remains poorly understood. The objective of the present research was to examine the association between auditory pitch processing and verbal and non-verbal cognitive abilities in children with ASD, compared with age- and IQ-matched typically developing (TD) children. Participants were 17 children with ASD and 19 TD children, matched on age and IQ. Participants were tested on performed a low-level pitch direction task and a higher-level melodic pitch global-local task. Verbal and non-verbal cognitive abilities were measured using the Verbal IQ and Performance IQ components of the Wechsler Abbreviated Scale of Intelligence (WASI). No group differences in performance were found on either auditory task or IQ measure. Furthermore, verbal abilities did not predict performance on the auditory tasks in either group. However, non-verbal abilities predicted performance on both of the auditory tasks in ASD and TD. This work contributes to a better understanding of sensory processing and cognitive reasoning in children with ASD and typically-developing children. Specifically, these results indicate that tonal pitch-based auditory processing is preserved in individuals with ASD with average IQ. These findings also suggest that auditory perception is related to non-verbal reasoning rather than verbal abilities in both ASD and TD, implying that there may be common perceptual-cognitive profiles in these subgroups of children with ASD that are similar to typical development. Accordingly, this work supports the idea that some individuals with ASD have 'islets of ability' amidst their sensory and cognitive difficulties. These results motivate future studies to examine whether similar perceptual-cognitive associations might be observed in a broader sample of individuals with ASD, such as those with language impairment or lower IQ.

Keywords: autism; auditory; pitch; cognitive; non-verbal reasoning; language; typical development

Table of Contents

List of tables

List of figures

List of abbreviations

ADI	Autism Diagnostic Interview - Revised
ADOS	Autism Diagnostic Observation Schedule
ASD	Autism Spectrum Disorder
EPF	Enhanced Perceptual Functioning
GL	Global-local
IQ	Intelligence quotient
NVIQ	Non-verbal intelligence quotient
PD	Pitch direction
TD	Typically-developing
VIQ	Verbal intelligence quotient
WCC	Weak Central Coherence
WASI	Wechsler Abbreviated Scale of Intelligence

Acknowledgments

I have been incredibly fortunate to have had exceptional mentors over these past two years. To each of them, thank you for your kindness throughout this process. I would like to express my gratitude to my supervisor, Dr. Krista Hyde, for welcoming me with open arms, and for her constant encouragement and support. It was an absolute delight to be a member of your laboratory.

I am indebted to my colleague and friend, Dr. Megha Sharda, for her invaluable mentorship and patience throughout our collaboration. My thesis has benefited tremendously from your knowledge and guidance. You teach me to be a better researcher every day.

I would also like to acknowledge my wonderful colleagues at the abcdlab and BRAMS, Dr. Nicholas Foster, Ana Tryfon, and Falisha Karpati, for taking the time from their hectic schedules to provide such thoughtful feedback on my thesis. Thanks to my precious lab mates, Carola Türk and Kevin Jamey, for their kindness. I have the pleasure to count you among my closest friends.

A final and special mention to my best friend, Esther Germain, for her unwavering belief in me, through thick and thin; I couldn’t have asked for a better companion on this journey

INTRODUCTION

Overview of Autism Spectrum Disorder (ASD)

The earliest descriptions of symptoms of an autism-like disorder emerged in 1943, in a report describing several children that appeared to share common characteristics, forming a particular "syndrome." These descriptions included withdrawal from the outside world, sensitivity to sounds, motions, and direct physical contact, as well as delayed or lack of acquired language (Kanner, 1943). Although there is marked variability in the symptomatology and presentation of this disorder, these earlier characteristics feature among today's definition of Autism Spectrum Disorder (ASD). ASD is a complex neurodevelopmental condition affecting 1 in 68 individuals (U.S. Centers for Disease Control and Prevention, 2014). The core features of ASD include impaired social communication as well as restricted and repetitive behaviours. In addition, recent diagnostic criteria include atypical sensory processing as an associate feature of ASD, as well as intellectual impairment as a severity specifier (American Psychiatric Association, 2013). With a vast majority of individuals with ASD presenting differences in sensory processing (Tomchek, Huebner & Dunn, 2014), and discrepant cognitive profiles (Joseph. Tager-Flusberg & Lord, 2002), perception-based studies of ASD are complementary to more traditional symptom-based studies. However, it is unclear how atypical perceptual processing in ASD contributes to other areas of functioning, such as language or cognitive abilities. Furthermore, knowledge of sensory processing in ASD is limited, particularly in the auditory domain. Accordingly, the main goal of the present study was to examine auditory perception in relation to verbal and non-verbal cognitive abilities in ASD versus typical development (TD).

Sensory perception in ASD

Efficiently processing the multisensory world around us requires intact sensory processing abilities. Interacting with our environment also involves processing relevant information while ignoring irrelevant cues. The core features of ASD supported by research on sensory perception has implied that individuals with ASD and typically-developing (TD) individuals tend to process the world differently. Hence, to capture these differences, past research has examined perception in various modalities and across different levels of processing in ASD relative to TD. In studies of sensory perception, a 'low-level' task requires processing of the most elementary features of a stimulus. Previous studies have reported that individuals with ASD are particularly apt at extracting the featural characteristics of a stimulus, as they enter the perceptual system. As such, there have been many reports of intact or enhanced sensory processing of low-level stimuli in various sensory domains in ASD relative to TD (Bertone, Mottron, Jelenic, & Faubert, 2005; Heaton, Hudry, Ludlow, & Hill, 2008). In contrast, a 'higher-level' task of sensory processing relies on greater efforts to integrate, manipulate, and make sense of patterns involving low-level information. Higher-order processing is crucial to navigate our sensory world, which is characterized by the ability to distinguish between the whole ("global") or detailed ("local") features of a stimulus. For example, in typical development, visual perception is often associated with seeing the forest (a global percept) before the trees (the local features). In other words, TD individuals tend to process global elements before local elements, which is termed 'global precedence effect' (for a review, see Simmons et al., 2009). In contrast, individuals with ASD often have difficulties processing complex stimuli and integrating low-level stimuli to form coherent global percepts. As a result, previous work on ASD has reported atypical processing in multiple sensory domains in tasks where the global or local features of a stimulus are incongruent (Bertone et al., 2005; Ouimet, Foster, & Hyde, 2012).

To date, most research investigating sensory difficulties in ASD have been limited to the visual domain. The study of atypical visual processing in ASD has been particularly of interest, given the characterization of ASD as a social deficit (Simmons et al., 2009). For instance, previous studies have shown that individuals with ASD display difficulties in facial recognition (Dawson, Webb, & McPartland, 2005; Schultz, 2005), as well as enhanced visual search skills (O'Riordan & Plaisted, 2001) relative to TD. Such findings provide meaningful examples of how perception-based studies are essential to better understanding the core symptoms observed in ASD. Previous studies on visual processing in ASD also support findings of enhanced local with typical or inferior global processing (Behrmann et al., 2006; Bertone, Hanck, Kogan, Chaudhuri, & Cornish, 2010; Caron, Mottron, Berthiaume, & Dawson, 2006; Dakin & Frith, 2005; Simmons et al., 2009).

The dichotomy in the presentation of visual skills in ASD has led to the elaboration of two predominant theories that propose to explain atypical sensory perception in ASD. The Enhanced Perceptual Functioning (EPF) model relies on the notion that individuals with ASD have a perceptual style that is more detail-oriented than TD individuals. This bias towards low-level perceptual mechanisms leads to an enhanced processing of the elementary characteristics of perceptual stimuli, but without necessarily impacting global processing. As a result, this model predicts superior low-level perception as well as local processing in ASD but intact global processing (Mottron, Dawson, Soulières, Hubert, & Burack, 2006). The Weak Central Coherence (WCC) theory also proposes that individuals with ASD display enhanced processing of low-level features of perceptual stimuli. However, the WCC model suggests that children with ASD have difficulty integrating local information into a meaningful global whole, leading to poorer global processing abilities (Frith, 1989). This advantage, however, may be due to impaired processing of complex information, such as integrating local features of a stimulus into a global whole (Shah and Frith, 1989; Bonnel et al., 2010). This theory might explain why individuals with ASD tend to have superior performance on tasks that depend on a local rather than a global processing strategy. Hence, the WCC is hypothesized to be the strategy behind superior performance in ASD on non-verbal reasoning tasks, such as the Block Design task (Stanutz, Wapnick, & Burack, 2014). While both the EPF and WCC theoretical models have served as important frameworks for understanding atypical perceptual processing in ASD, particularly in the visual domain, the WCC model is limited in that its theoretical contributions have not yet been applied to examine atypical perceptual processing across both visual and auditory domains or the effect of stimulus complexity (low versus high) on sensory processing in ASD (Ouimet et al., 2012). Hence, the EPF model may serve as a more comprehensive framework in the context of atypical auditory perception in ASD across levels of stimulus complexity (Mottron, 2006).

Although much research on atypical sensory perception in ASD has focused in the visual domain, more insight on perception in the auditory domain is pivotal for a better understanding of atypical perception in ASD across modalities. One puzzling example of atypical auditory perception in ASD is that those on the autism spectrum demonstrate outstanding abilities in pitch processing, as described by a high incidence of absolute pitch present in this population (see Mottron, et al. 2013 for a review; DePape, Hall, Tillman & Trainor, 2012). In contrast, in the general population, absolute pitch occurs extremely rarely, found in only 1 in 10, 000 individuals (Takeuchi & Hulse, 1993). The striking difference in pitch perception between ASD and TD populations provides compelling motivation to further investigate atypical auditory perception in ASD, within the context of the wide array of social and communication deficits that characterize this population. In the auditory domain, individuals with ASD have been shown to demonstrate intact or even enhanced processing of simple and low-level sensory information (see Kellerman, Fan, & Gorman, 2005; O'Connor, 2012; Ouimet, Foster, Tryfon, & Hyde, 2012 for reviews). For instance, many studies have shown that individuals with ASD present enhanced pitch processing abilities in the context of low-level auditory tasks, such as pitch discrimination, which might result from a superior ability in extracting low-level information from sound stimuli (Bonnel et al., 2003, 2010; Heaton, Hermelin, & Pring, 1998; Heaton et al., 2008; Jones et al., 2009; Mayer, Hannent, & Heaton, 2014; O'Riordan & Passetti, 2006). Individuals with ASD also tend to exhibit impaired or atypical performance in tasks that require higher cognitive demands (i.e. pattern recognition, comprehension, attention). As such, enhanced pitch processing abilities in ASD have been shown in the context of high-level tasks such as auditory global-local pitch processing (Mottron, Peretz, & Ménard, 2000) and detection of contour violations in melodies (Heaton, Pring, & Hermelin, 2001). Somewhat analogous to their visual profiles, individuals with ASD tend to process auditory local features before global ones, displaying an advantage in local processing (Bouvet, Simard-Meilleur, Paignon, Mottron, & Donnadieu, 2014; Mottron et al., 2000). This is further compounded by difficulties in temporal integration as well as modulation and filtering of sensory information (Alcàntara, Weisblatt, Moore, & Bolton, 2004; Stevenson et al., 2014). In sum, individuals with ASD show mixed perceptual profiles consisting of intact, enhanced, as well as impaired abilities in both auditory and visual domains. Relative to vision, however, the distinction between low- and higher-level auditory processing remains unclear. As such, this master's thesis includes a range of auditory tasks varying in complexity to better characterize auditory processing in ASD and TD.

Cognitive abilities and sensory processing in ASD

Based on previous findings, there has been increasing interest in exploring how perceptual processing interacts with other domains of atypical functioning in ASD, such as language and cognitive abilities. A better understanding of how these domains interact may not only provide insight into the ASD phenotype, but may also lead to a better understanding of individual differences across the autism spectrum. Hence, another objective of this Master's thesis aims is to examine sensory-cognitive processing in ASD and TD children.

Individuals with ASD often display very uneven cognitive profiles (Kanner, 1972), with intellectual disability present in nearly half the ASD population (Charman et al. 2011). Even among those without intellectual disability, there is marked variability in the presentation of verbal and non-verbal cognitive profiles in ASD (Joseph et al., 2002; Black, Wallace, Sokoloff, & Kenworthy, 2014). The Wechsler intelligence scales, such as the Wechsler Abbreviate Scale of Intelligence (WASI), are a common tool to estimate an individual's general intelligence, which include both verbal and non-verbal intelligence measurements (Wechsler 1999, 2011). Verbal intelligence (VIQ) measures verbal reasoning abilities using the examiners' acquired knowledge of verbal concepts, whereas non-verbal or performance intelligence (NVIQ; PIQ) relies on the examiner's fluid reasoning abilities (Wechsler, 2011). In TD, past research has shown that there is a strong link between verbal and non-verbal abilities (Anderson et al., 2007; Charman et al., 2005; Turner, Stone, Pozdol, & Coonrod, 2006). In ASD, however, the profiles of verbal and non-verbal cognitive functioning are highly variable, which is further complicated by language and communication difficulties in ASD (Howlin, Savage, Moss, Tempier & Rutter, 2014).

Language impairments are also extremely diverse across the population of ASD, in addition to being a defining feature in ASD presentation (Hudry et al., 2010; Pickles, Anderson, & Lord, 2014). Some individuals with ASD never fully acquire functional language (Gillberg & Coleman, 2000; Klinger, Dawson, & Renner, 2002) while others will have well-developed verbal skills (Boucher, 2003; Kjelgaard & Tager-Flusberg, 2001). In typical-development, language acquisition involves extracting semantic information from auditory content, while allocating resources towards both perceptual and higher-order information (Mayer et al., 2014). In contrast, in infants with ASD, there seems to be an initial bias towards low-level perceptual information rather than more complex stimuli requiring higher-order structure, which may hinder the development of language processing (Eigsti & Fein, 2013; Mayer et al., 2014; O'Riordan & Passetti, 2006). To better understand individual differences across the ASD phenotype, it is crucial to examine how atypical sensory processing contributes to the core features observed in ASD. On one hand, in typically-developing children, pitch discrimination has been associated with receptive vocabulary (Mayer et al., 2014) and with phonological skills (Grube, Kumar, Cooper, Turton, & Griffiths, 2012). In addition, there is increasing evidence linking music training to literacy skills in TD (Gordon, Fehd & McCandliss, 2016). On the other hand, there have been mixed evidence regarding the association between language impairments and sensory processing in ASD. Previous evidence has shown that language impairments in ASD may be associated with poorer auditory discrimination abilities (Loui, Kroog, Zuk, Winner, & Schlaug, 2011; McArthur & Bishop, 2004) as well as enhanced pitch processing abilities (Bonnel et al., 2010; Eigsti & Fein, 2013; Jones et al., 2009). Furthermore, studies have shown that semantic and pragmatic difficulties present in ASD may be associated with an inclination towards fine-grained processing of speech-signals (Schreibman, Kohlenberg, Britten, 1986; Järvinen-Pasley, Wallace, Ramus, Happé, & Heaton, 2008), thereby highlighting the importance of exploring the association between language abilities and auditory perception in ASD. Previous work has also shown that even in higher-functioning individuals with ASD, atypical sensory sensitivity can impair verbal skills (Mayer et al., 2014). While there is increasing evidence linking verbal abilities to musical perception in TD children, there is not yet a consensus on how language abilities relate to auditory processing in ASD. Hence, these discrepant findings motivate a further investigation of how verbal abilities are associated with sensory perception in ASD; in particular, to better characterize how sensory sensitivity may emerge within subgroups of individuals with ASD, and relative to TD individuals.

In terms of non-verbal cognitive abilities, previous work also supports uneven cognitive profiles in ASD, mostly in favour of greater non-verbal ability in ASD (Joseph et al., 2002; Black et al., 2014). A task that is commonly used to assess non-verbal reasoning in ASD is the Block Design task, an IQ subtest that requires focusing on local elements within a visual pattern while ignoring its global aspects (Wechsler, 1974, 1981; Mitchell & Ropar, 2004). Based on previous findings, individuals with ASD are likely to perform significantly better in the Block Design task relative to TD controls (Caron et al., 2006; Gilchrist et al., 2001; Goldstein, Beers, Siegel, & Minshew, 2010; Meilleur, Jelenic, & Mottron, 2015; Meilleur, Berthiaume, Bertone, & Mottron, 2014; Ropar & Mitchell, 2001; Rumsey & Hamburger, 1988; Shah & Frith, 1993; Siegel, Minshew, & Goldstein, 1996; Venter, Lord, & Schopler, 1992). However, superior performance in Block Design relative to other tasks has been found consistently, particularly in higher-functioning individuals with ASD (Kaland, Mortensen, & Smith, 2007; Ropar & Mitchell, 2001). Such heterogeneous findings suggest that individual differences may underlie cognitive processing strategies in ASD, which may also extend to different modalities, such as auditory perception. However, very few studies have examined the association between cognitive skills and auditory perception in ASD and TD. One study reported an association between musical memory and non-verbal fluid reasoning strategies in children with ASD relative to age- and IQ-matched controls (Stanutz et al., 2014). Another recent study found that better pitch discrimination abilities are not associated with better performance on non-verbal reasoning tasks, such as the Block Design, in ASD (Meilleur et al., 2015). Taking into account that ASD is associated with a broad range of cognitive strengths and weaknesses, as well as the inconsistent findings across the few studies, more research is required to better understand whether these uneven cognitive profiles reflect differential information processing strategies in ASD. The range of auditory tasks used in the present study will also help elucidate perceptual-cognitive relationships of this nature in ASD and TD.

Study objectives

The overall goal of my Master's thesis was to better characterize the association between auditory pitch perception and verbal and non-verbal cognitive abilities in ASD versus TD. To date, studies on auditory perception in ASD have examined either low or high-level processing in isolation. Past research using complex auditory paradigms has shown that individuals with ASD tend to exhibit impaired or atypical performance, especially in tasks that require higher cognitive demands (i.e. pattern recognition, comprehension, attention). As much remains to be understood regarding atypical auditory processing in ASD, it is crucial to use a range of stimuli differing in task complexity (low versus high) to better capture potential differences in processing strategies in ASD relative to TD (O'Connor, 2012). Hence, given the growing evidence supporting atypical auditory perception in ASD, a more comprehensive understanding of the role of stimulus and task complexity can be gained by comparing both low- and higher-level processing in ASD relative to TD. The auditory tasks used in this study offer a range of complexity that might address mixed findings in previous studies, and may be important to examine whether these associations differ between low- and higher-levels of auditory perception. In addition, previous studies have reported inconsistent findings with regard to the presence of atypical processing in ASD, in both areas of auditory perception and cognition. In particular, very few studies have examined perceptual-cognitive associations in the auditory domain in ASD, crucial to gain a better understanding of the ASD phenotype and how they may contribute to the core symptoms presented in ASD. Finally, building on the findings of this study may provide a framework for future research on atypical sensory processing in ASD, which in turn, can potentially guide targeted auditory-based interventions in clinical populations such as ASD.

Aims & Hypotheses

The main objective of the present study was to examine the relationship of both low- and high-level pitch processing with verbal and non-verbal abilities in ASD versus TD children. In the present study, the low-level pitch direction (PD) task consists of simple pitch judgments on tone pairs, whereas the high-level global-local (GL) task involves pattern recognition using more complex melodic stimuli and includes judgments of both local and global pitch structure (Justus & List, 2005; Ouimet et al., 2012).

Aim 1 was to examine performance differences across low- and high-level auditory tasks and between verbal and non-verbal cognitive measures in ASD versus TD children. Based on previous literature, it was expected that the ASD group would exhibit poorer verbal abilities and enhanced non-verbal abilities, whereas TD would show the opposite cognitive profile. It was also expected that the ASD group would show enhanced performance relative to TD on the low-level PD task and on the local component of the GL task without necessarily impacting performance on the global condition of the GL task, consistent with the EPF framework of perception in ASD.

Aim 2 was to examine the relationship between verbal abilities and performance on auditory PD and GL tasks. Based on previous findings, it was expected that better performance on the PD task would be associated with better verbal abilities in TD (Grube et al, 2012; Mayer et al., 2014). In contrast, in ASD performance on the PD task was expected to be related to poor verbal abilities due to an over-emphasis on the low-level features of auditory stimuli (Bonnel et al., 2010, Frith, 1989). On the higher level GL task, performance was expected to be positively related to verbal ability in both groups (Heaton et al., 2008a).

Aim 3 was to examine the relationship between non-verbal abilities and performance on auditory PD and GL tasks. For both the low-level and higher-level auditory tasks, it was expected that performance would be positively correlated with non-verbal abilities in ASD and TD (Meilleur et al., 2014).

Auditory pitch perception in autism spectrum disorder is associated with superior non-verbal abilities

Rakhee Chowdhury[1*], Megha Sharda[1*], Nicholas E.V. Foster[1], Esther Germain[1], Ana Tryfon[1, 2]

Krissy Doyle-Thomas[3], Evdokia Anagnostou[3] and Krista L. Hyde[1,2]

Affiliations

1) International Laboratory for Brain Music and Sound Research (brams.org), University of Montreal, Montreal, Canada

2) Faculty of Medicine, McGill University, Montreal, Canada

3) Holland Bloorview Kids Rehabilitation Hospital, University of Toronto, 150 Kilgour Road, Toronto, ON, M4G 1R8, Canada.

Abstract

Atypical sensory perception and cognitive profiles are common features of Autism Spectrum Disorder (ASD). However, previous findings on sensory processing in ASD, particularly in the auditory domain, are mixed. Accordingly, auditory perception and its relation to verbal and non-verbal cognitive abilities in ASD remains poorly understood. Here, children with ASD, and age- and IQ matched typically-developing (TD) children, were tested on a low- and a higher-level pitch processing task. Verbal and non-verbal cognitive abilities were measured using the Wechsler Abbreviated Scale of Intelligence (WASI). There were no group differences in performance on either auditory task or IQ measure. However, non-verbal abilities, rather than verbal skills, predicted performance on auditory tasks in both ASD and TD. These results suggest that auditory perception is related to non-verbal reasoning rather than verbal abilities in ASD and TD children. In addition, these findings provide evidence for preserved tonal pitch processing in school-age children with ASD with average IQ, supporting the idea that some individuals with ASD have 'islets of ability' amidst their sensory and cognitive difficulties. Future directions involve examining whether similar perceptual-cognitive relationships might be observed in a broader sample of individuals with ASD, such as those with language impairment or lower IQ.

Keywords: autism; auditory; pitch; cognitive; non-verbal reasoning

Introduction

Autism Spectrum Disorder (ASD) is a complex neurodevelopmental condition that affects 1 in 68 individuals (U.S. Centers for Disease Control and Prevention, 2014). The core features of ASD include impaired social communication as well as restricted and repetitive behaviours. In addition, atypical sensory processing is a common feature of ASD according to the Diagnostic and Statistical Manual of Mental Disorders (DSM-V; American Psychiatric Association, 2013). However, research on sensory processing in ASD is limited, particularly in the auditory domain. Furthermore, individuals with ASD often display very uneven intellectual profiles (Kanner, 1972), with approximately half the ASD population having an intellectual disability (Charman et al. 2011). Even among those without intellectual disability, there is significant variability in verbal and non-verbal profiles (Joseph. Tager-Flusberg & Lord, 2002; Black, Wallace, Sokoloff, & Kenworthy, 2014). Accordingly, the main goal of the present study was to examine auditory perception in ASD versus typical development (TD), particularly in relation to verbal and non-verbal cognitive abilities.

Sensory perception in ASD

Intact sensory processing is crucial to effectively interact with the multisensory world around us. However, individuals with ASD often have difficulties processing complex stimuli and integrating low-level stimuli to form coherent global percepts. In particular, previous work on ASD has reported atypical processing in both visual and auditory domains in tasks where the whole ("global") or parts ("local") of a stimulus are incongruent (Bertone, Mottron, Jelenic, & Faubert, 2005; Ouimet, Foster, & Hyde, 2012). This is further compounded by difficulties in temporal integration as well as modulation and filtering of sensory information (Alcàntara, Weisblatt, Moore, & Bolton, 2004; Stevenson et al., 2014). Previous evidence suggests that while TD individuals tend to process global elements before local elements ("global precedence effect"), individuals with ASD tend to process auditory local features before global ones, leading to an advantage in local processing (Bouvet, Simard-Meilleur, Paignon, Mottron, & Donnadieu, 2014; Mottron et al., 2000). Taken together, individuals with ASD have shown superior pitch processing on low-level and tonal pitch discrimination tasks (Bonnel et al., 2003, 2010; Heaton, Hermelin, & Pring, 1998; Heaton et al., 2008; Jones et al., 2009; Mayer, Hannent, & Heaton, 2014; O'Riordan & Passetti, 2006), and intact (Foster et al., 2016) or enhanced (Bouvet et al., 2014; Mottron et al., 2000) processing of local-based pitch judgements in higher-level melodic global-local tasks relative to TD.

In sum, individuals with ASD show mixed sensory profiles in both the auditory and visual domains. This dichotomous profile of sensory processing in ASD, consisting of both diminished and enhanced processing, has been studied in the context of two main theories of neurocognitive functioning in ASD. The Weak Central Coherence (WCC) theory, proposes that children with ASD have a preference for local information processing, yet have difficulty integrating local information into a meaningful global whole, leading to poorer global processing abilities (Frith, 1989). In contrast, the Enhanced Perceptual Functioning (EPF) model proposes that superior low-level perception leads to enhanced local or detailed-based processing, but without necessarily impacting global processing (Mottron, Dawson, Soulières, Hubert, & Burack, 2006). Support for the EPF model comes from findings of enhanced simple and local-based processing in the visual (e.g., Behrmann et al., 2006; Bertone, Hanck, Kogan, Chaudhuri, & Cornish, 2010; Caron, Mottron, Berthiaume, & Dawson, 2006; Dakin & Frith, 2005; Simmons et al., 2009) and auditory (Mottron et al., 2000) domains. While both the EPF and WCC theoretical models have served as important frameworks for understanding atypical perceptual processing in ASD, the EPF model may serve as a more comprehensive framework in the context of atypical auditory perception in ASD across levels of stimulus complexity (Mottron, 2006).

Association between perception and cognition in ASD

Based on previous findings, there has been increasing interest in exploring how atypical sensory processing interacts with other domains of functioning in ASD, such as cognitive abilities. Thus, the main objective of the present research was to better understand perceptual-cognitive phenotypes in ASD across low- and higher-level auditory tasks.

Individuals with ASD demonstrate mixed cognitive profiles (Charman et al., 2005; Farley et al., 2009; Koyama, Tachimori, Osada, Takeda, & Kurita, 2007, Joseph et al., 2002; Black et al., 2009). As such, recent diagnostic criteria specify the presence or absence of intellectual impairment to better characterize ASD symptomatology. This severity specifier is further described by separately assessing the individual's verbal and non-verbal aptitude (American Psychiatric Association, 2013). A common tool to estimate an individual's general intelligence is the Wechsler intelligence scales, such as the Wechsler Abbreviate Scale of Intelligence (WASI), which include verbal IQ (VIQ) as well as performance or non-verbal IQ (NVIQ) subtests (Wechsler 1999, 2011). Verbal intelligence, as measured by standardized cognitive tests, does not provide a comprehensive measure of language, but rather relies on an individual's receptive and expressive vocabulary (Anderson et al., 2007). Hence, the child is measured on his or her ability to form verbal concepts using their knowledge of words. Non-verbal intelligence, in contrast, generally relies on perceptual reasoning abilities, and its measures are often visual in nature (Wechsler 1999, 2011). In TD, past research has shown that there is a strong relationship between verbal and non-verbal abilities (Anderson et al., 2007; Charman et al., 2005; Turner, Stone, Pozdol, & Coonrod, 2006). In ASD, however, there is evidence of marked variability in cognitive profiles. For instance, younger children with ASD may show a mixed profile of poorer verbal abilities (Hudry et al., 2010) and enhanced non-verbal reasoning compared to TD (Mayes & Calhoun, 2003). Accordingly, there have been many reports of individuals with ASD performing significantly better than TD on the Block Design task (Caron et al., 2006; Gilchrist et al., 2001; Goldstein, Beers, Siegel, & Minshew, 2010; Meilleur, Jelenic, & Mottron, 2015; Meilleur, Berthiaume, Bertone, & Mottron, 2014; Rumsey & Hamburger, 1988; Shah & Frith, 1993; Siegel, Minshew, & Goldstein, 1996; Venter, Lord, & Schopler, 1992), an IQ subtest of non-verbal reasoning that requires focusing on local elements within a visual pattern while ignoring its global aspects (Mitchell & Ropar, 2004). Better performance on the Block Design task is characterized by the framework proposed by the WCC theory, which predicts an advantage in featural processing at the expense of global information (Shah & Frith, 1983, Jonge, Kemner, Naber, van Engeland, 2009). This advantage in non-verbal abilities appears to be particularly robust in individuals with ASD with delayed language acquisition (Soulieres, Zeffiro, Girard, & Mottron, 2011). On the other hand, there have also been reports of higher verbal than non-verbal ability in individuals with ASD (Joseph et al., 2002; Black et al., 2009). Hence, evidence from previous literature suggests that ASD is associated with a broad range of cognitive strengths and weaknesses, yet it is unclear whether these uneven cognitive profiles reflect differential information processing strategies in ASD.

In addition to these mixed cognitive profiles in ASD, the relationship between cognitive functioning and sensory processing in ASD is unclear. While there is increasing evidence that links music training to literacy skills in TD children (Gordon, Fehd, & McCandliss, 2015), there is not yet a consensus on how language abilities relate to auditory processing in ASD. One previous study found that auditory pitch discrimination was not associated with receptive vocabulary in individuals with ASD, but was positively associated with non-verbal reasoning (Mayer et al. 2014). In the TD group, however, previous revealed a positive association between verbal abilities and pitch discrimination (Mayer et al. 2014; Grube, Kumar, Cooper, Turton, & Griffiths, 2012). Another study exploring the link between pitch discrimination ability and non-verbal fluid reasoning ability reported that children with ASD exhibited superior pitch discrimination in a melodic context compared to age- and IQ-matched TD children (Stanutz, Wapnick, & Burack, 2014). These results are consistent with the EPF model of ASD which posits that contextual information processing remains preserved in ASD (Mottron et al., 2006). The same group also found that melodic memory ability was correlated with measures of non-verbal fluid reasoning ability in ASD (Stanutz et al., 2014). However, contradictory findings also suggest that enhanced pitch discrimination abilities in ASD do not necessarily co-occur with a perceptual strength in non-verbal tasks, such as the Block Design task (Meilleur et al., 2015). Thus, verbal and non-verbal abilities appear to affect auditory perception in ASD and TD differently, but further study is required across a range of auditory tasks to better understand perceptual-cognitive relationships in ASD.

Study objectives

The main objective of the present study was to examine the relationship between low-level auditory perception with verbal, non-verbal and language abilities in ASD compared to TD. Here, the low-level pitch direction (PD) task consists of simple pitch judgments on tone pairs, whereas the high-level global-local (GL) task involves pattern recognition using more complex melodic stimuli and includes judgments of both local and global pitch structure (Justus & List, 2005; Ouimet et al., 2012).

Aim 1 was to examine performance differences across low- and high-level auditory tasks and between verbal and non-verbal cognitive measures in ASD versus TD children. Based on previous literature, it was expected that the ASD group would exhibit poorer verbal abilities and enhanced non-verbal abilities, whereas TD would show the opposite cognitive profile. It was also expected that the ASD group would show enhanced performance relative to TD on the low-level PD task and on the local condition of the GL task without necessarily impacting performance on the global condition of the high-level GL task, consistent with the EPF framework of perception in ASD.

Aim 2 was to examine the relationship between verbal abilities and performance on auditory PD and GL tasks. Based on previous findings, it was expected that better performance on the PD task would be associated with better verbal abilities in TD (Grube et al, 2012; Mayer et al., 2014). In contrast, in ASD performance on the PD task was expected to be related to poor verbal abilities due to an over-emphasis on the low-level features of auditory stimuli (Bonnel et al., 2010, Frith, 1989). On the higher level GL task, performance was expected to be positively related to verbal ability in both groups (Heaton et al., 2008a).

Aim 3 was to examine the relationship between non-verbal abilities and performance on auditory PD and GL tasks. For both the low-level and higher-level auditory tasks, it was expected that performance would be positively correlated with non-verbal abilities in ASD and TD (Meilleur et al., 2014).

In sum, this work serves to characterize auditory perception in ASD across levels of processing, particularly in the context of verbal and non-verbal cognitive abilities, In turn, these findings can help to further refine perceptual-cognitive phenotypes in ASD.

Methods

Participants

Two groups of children participated in the present study: 1) 17 children with ASD and 2) 19 TD children, matched on age (mean age 13.3 years, SD 2.3, range 9-18 years) and IQ (mean IQ 113.5, SD 13.6, range 78-146) (see Table 1 for participant characteristics). Participants were recruited as part of the NeuroDevNet ASD Demonstration Project, a multi-site initiative that aims to examine the development of brain structure and behaviour in children with ASD (Zwaigenbaum et al., 2011). All children were recruited and tested at one of two sites: 1) at the Montreal Neurological Institute (Montreal, Canada) and 2) the Holland Bloorview Kids Rehabilitation Hospital (Toronto, Canada). Individuals with ASD were diagnosed by expert opinion and diagnoses were supported by standard diagnostic measures (DSM-IV-TR, American Psychiatric Association 2000; Autism Diagnostic Observation Schedule, ADOS, Lord et al., 1989; Autism Diagnostic Interview-Revised, Lord, Rutter, & Lecouteur, 1994). The ADOS was administered using modules 3 and 4 of the ADOS/ ADOS-2. IQ was assessed using the full-scale score on the Wechsler Abbreviated Scale of Intelligence (WASI) or WASI-II (Wechsler 1999, 2011). Exclusion criteria included an IQ score below 70, a gestational age of 35 weeks or less, and a medical history of neurological disease. Additional exclusion criteria for the TD group included a history of neurological or psychiatric illness and a family history of ASD. The present study was approved by local ethics committees at each site. All participants were compensated for their time. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. All guardians provided written informed consent and participants above the age of 14 provided assent.

Table 1: Participant characteristics

	ASD (n = 17, 0*)			TD (n = 19, 11 F*)			
	Mean	SD	Range	Mean	SD	Range	p-value
Age (years)	13.7	2.3	9.3 - 17.9	12.9	2.3	9.1 - 16.2	0.27
Full-scale IQ[a] (FSIQ[b])	110.8	18.3	78 - 146	115.8	8.1	96 - 127	0.32
Non-verbal IQ (NVIQ)	112.4	18.7	84 - 136	115.5	12.6	89 - 137	0.58
Block Design subtest	57.2	11.9	35 - 72	60.9	8.0	44 - 77	0.31
Matrix Reasoning	56.8	9.2	39 - 70	57.4	7.0	38 - 65	0.81
Verbal IQ (VIQ)	106.7	18.6	76 - 146	113.2	10.3	93 - 131	0.23
Vocabulary	51.7	11.3	34 - 72	56.3	9.7	27 - 68	0.19
Similarities	56.3	12.0	33 - 78	59.8	5.3	51 - 72	0.29
ADOS[c] composite score	9.4	4.5	2 - 19	-	-	-	-

SD = standard deviation

* Since no sex-related performance differences were found in the TD group, both males and females were included in the current TD sample.

a. IQ: Intelligence Quotient

b. FSIQ, NVIQ, and VIQ and their subtests (Block Design, Matrix Reasoning, Vocabulary, Similarities), were measured using Wechsler's Abbreviated Scale of Intelligence (WASI)

c. ADOS: Autism Diagnostic Observation Schedule (ADOS Composite Score: Social Reciprocity + Communication)

Tasks

All participants were tested on a low-level auditory pitch direction (PD) task, a high-level auditory global-local (GL) task, as well as verbal and non-verbal subtests of the WASI. Both tasks were presented using Presentation software (Neurobehavioral Systems, Albany, CA, http://www.neurobs.com). The order of the tasks was counterbalanced across participants. The experiment was administered on a laptop computer. The stimuli were presented binaurally through Sennheiser HD 25-1 II headphones at a comfortable volume. Participant responses were registered by clicking the left or right button of a computer mouse. Correct/incorrect responses were reported by the Presentation software.

Low-level pitch direction task

Low-level auditory perception was measured using a pitch direction (PD) task previously used in blind adults (Gougoux et al., 2004). Pitch distances and temporal rates were parametrically manipulated and varied by trial, such that a smaller pitch distance or a faster temporal rate between the presented tones increased the trial difficulty. In each trial, participants heard pairs of tones that differed in pitch and were prompted to choose whether the second tone had a lower or higher pitch compared to the first one. In the reference condition, the pitch difference was 150 cents (1.5 semitones) and the duration of each tone was 333 milliseconds (Figure 1). Eight additional conditions were created by parametrically manipulating the temporal and spectral domains: either by successively dividing tone duration by two (resulting in durations of 167, 83, 42, or 21ms) or by dividing the frequency spacing between the tones by two (resulting in pitch differences of 75, 38, 19, or 9 cents). The task was presented in 4 blocks. Within each block, there were 9 levels of pitch/temporal difficulty, with 8 stimuli each, for a total of 72 trials. The order of stimuli was randomized within each block. Prior to testing, participants performed 18 practice trials to ensure their understanding of the task. Participants were instructed to respond with their dominant hand and to press one button of a computer mouse if they perceived the pattern to be going up (if the second sound was higher in pitch), and another button if they believed the pattern was going down (if the second sound was lower in pitch). Participants were asked to respond as quickly and accurately as they could. Accuracy was assessed using the percentage of correct responses (mean percent correct) made by the participants. The average duration of the task was 30 minutes and breaks were taken when required.

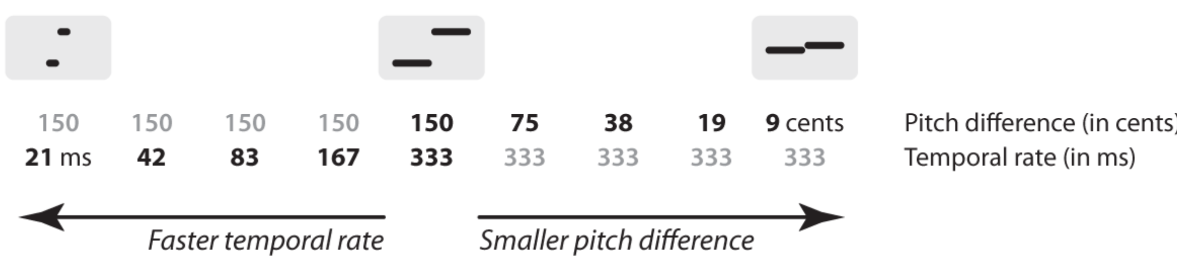

Figure 1: Schematic of low-level pitch direction (PD) task stimuli. Examples of tone pairs varying in duration and pitch difference are shown.

High-level global-local task

High-level auditory perception was measured using an auditory global-local (GL) task, which was previously used by our research group in a sample of TD adults (Ouimet, Foster, & Hyde, 2012) and another partially overlapping sample of children with ASD (Foster et al., 2016). The stimuli and procedure have been previously described in detail in Foster et al. (2016). In this task, participants heard three-tone triplet sequences combined to form a sequence of nine harmonic tones. The local level was defined as the pattern within a triplet, and the global level was defined by the pattern created by the first tones of each of the three triplets (Figure 2). Each of the local and global levels was presented in three different types of sound patterns: "up," "down," and "neutral." Participants were asked to judge whether the sound pattern went up or down, while paying attention to either the global or local stimulus condition. In other words, participants completed one block in which they were instructed to direct their attention to the global level (the first tone of each triplet pattern) while ignoring the local levels, and another block in which they were instructed to direct their attention to the local level (the pattern within a triplet), while ignoring the global level. For each of the global and local blocks, six auditory stimuli (comprising 2 congruent, 2 incongruent-neutral and 2 incongruent-opposite stimuli) were presented 12 times for a total of 72 trials per block. This included three "up" stimuli and 3 "down" stimuli (with respect to the target global or local level), so that performance at chance would be 50%. In the congruent stimulus type (Figure 2), the same pattern was presented at both the local and global level, such that the entire sequence of nine harmonic tones either ascended, descended, or remained neutral. In the incongruent-neutral stimulus type, either the global or local level remained at the same pitch while the other ascended or descended. In the incongruent-opposite stimulus type, opposite pattern types were presented at the local and global levels. Participants performed 21 practice trials before each block. The order of trials was randomized in each block, the target feature (local/global level or up/down pattern) was counterbalanced by block, and the order of stimulus types (congruent, incongruent-neutral, incongruent-opposite) was randomized within blocks. Participants were instructed to respond using their dominant hand as quickly and accurately as they could. Button-finger assignment was counterbalanced.

For the global and local conditions of the auditory task, accuracy was assessed using the percent of correct responses made by the participants, calculated separately for each condition. The task lasted about 30 minutes and breaks were taken when required.

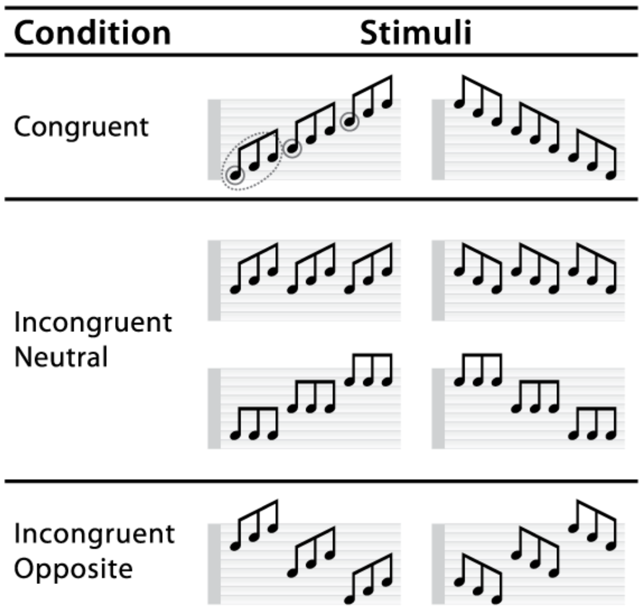

Figure 2: Schematic of the high-level global-local (GL) task stimuli. The global level was defined as the first tone of each triplet pattern (solid circle), and the local level was defined as the triplet pattern (dashed circle). Adapted from Foster et al, 2016.

Verbal and non-verbal cognitive abilities

Verbal and non-verbal cognitive abilities were assessed in all participants using the WASI. Verbal cognitive abilities were assessed using the Verbal IQ (VIQ) subscale of the WASI. In the Vocabulary subtest of the VIQ, participants were evaluated on word knowledge and verbal concept formation, while the Similarities subtest measured verbal reasoning and concept formation (Wechsler 1999).

Non-verbal cognitive abilities were assessed using the Performance IQ subscale of the WASI, henceforth referred to as non-verbal IQ (NVIQ), which includes the Block Design and Matrix Reasoning subsets. The Block Design subtest consists of a set of 13 modeled or printed two-dimensional geometric patterns that the participant replicates within a specified time limit using two-color cubes: some red, some white, and some half red/half white. Participants are tested on their ability to analyse and synthesize abstract visual stimuli. In the Matrix Reasoning subtest, participants are asked to identify the missing element that completes a pattern. Participants are thus evaluated on fluid intelligence, broad visual intelligence, spatial abilities and classifications, knowledge of the relationship between parts and the whole, simultaneous processing, and perceptual organization (Wechsler 1999).

Data analyses

Mean accuracy (percent correct) scores were computed for the PD and GL tasks for both ASD and TD. Statistical analyses were conducted using IBM SPSS Statistics, Version 22.0 (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp.). Results are reported at a significance level of $p < .05$ and corrected for multiple comparisons where relevant using Bonferroni correction. Group difference in performance on the auditory tasks between ASD and TD was assessed using t-tests on mean percent correct scores, averaged over all conditions. To examine the relationship between verbal and non-verbal cognitive abilities, and performance on each of the auditory tasks, univariate general linear models were used. All continuous covariates (age, VIQ and NVIQ) were mean-centered prior to the analyses. Initial analyses showed that performance did not differ depending on participants' age, gender, or the testing site. Consequently, these variables were not included in the above main models. Separate models for each dependent variable (task performance on low-level PD, high-level local, high-level global) were used for both cognitive measures (VIQ, NVIQ) as shown below. A total of 6 planned models were tested. Where effects were significant, additionally post-hoc models were tested to further understand the role of each cognitive subtest. These were corrected using Bonferroni tests.

$$Task\ Performance = b0 + b1 * Group + b2 * IQ + b3 * (Group \times IQ) + \varepsilon$$

Results

Performance on auditory PD and GL tasks by group

No group differences between ASD and TD were found in mean accuracy on the PD task (t_{34} = 0.63, p = .53), the GL task overall (t_{34} = 0.69, p = .50), the global condition of the GL task alone (t_{34} = 0.48, p = .64) or the local condition of the GL task (t_{34} = 0.59, p = .56) (Figure 3).

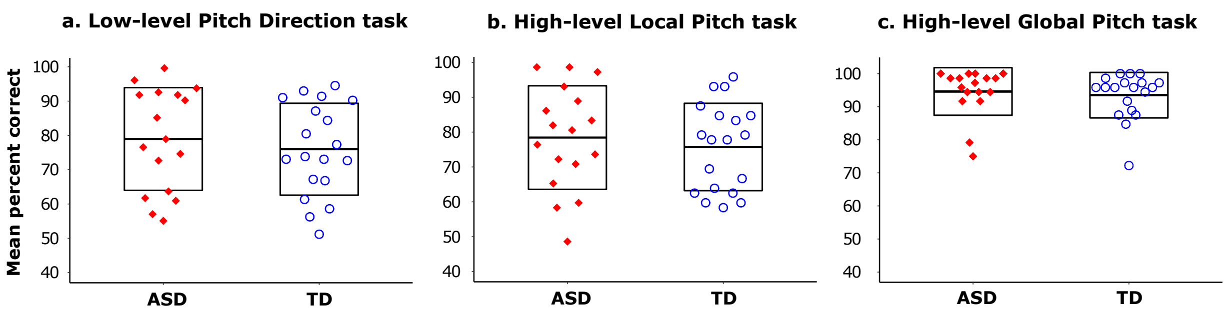

Figure 3: Performance on auditory pitch direction (PD) and global-local (GL) tasks in ASD and TD. No differences in mean accuracy between ASD and TD groups were found on a) the PD task, b) the high-level global GL task, c) the high-level local GL task (all p > .05). Boxes indicate mean value +/- 1 standard deviation.

Performance on cognitive measures by group

No group differences between ASD and TD were found on VIQ (t_{29} = 0.62, p = .23) and on subtests: Vocabulary (t_{34} = 1.35, p = .18) or Similarities (t_{29} = 1.08, p = .29). No differences between ASD and TD were found on NVIQ (t_{29} = 0.57, p = .58) and subtests: Block Design (t_{29} = 1.02, p = .32) or Matrix Reasoning (t_{34} = 0.24, p = .81).

Pitch perception and verbal abilities in ASD and TD

To study the relationship between verbal ability and auditory task performance, univariate general linear models were used. The analysis between PD performance and VIQ (Figure 4a) revealed no significant main effect of group ($F_{(1,27)} = 0.44$, $p = .51$) or VIQ ($F_{(1,27)} = 0.09$, $p = .77$), as well as no interaction effect between group and VIQ ($F_{(1,27)} = 0.99$, $p = .33$).

Similarly, for the local condition of the GL task, there was no main effect of group ($F_{(1,27)} = 1.37$, $p = .25$) or VIQ ($F_{(1,27)} = 1.68$, $p = .21$) as well as no interaction effect between group and VIQ ($F_{(1,27)} = 1.04$, $p = .32$; Figure 4b).

Analysis of the relationship between the global condition of the GL task and VIQ revealed no main effect of group ($F_{(1,27)} < 0.001$, $p = .98$) or VIQ ($F_{(1,27)} = 0.31$, $p = .58$) and no interaction effect between group and VIQ ($F_{(1,27)} = 0.10$, $p = .75$; Figure 4c).

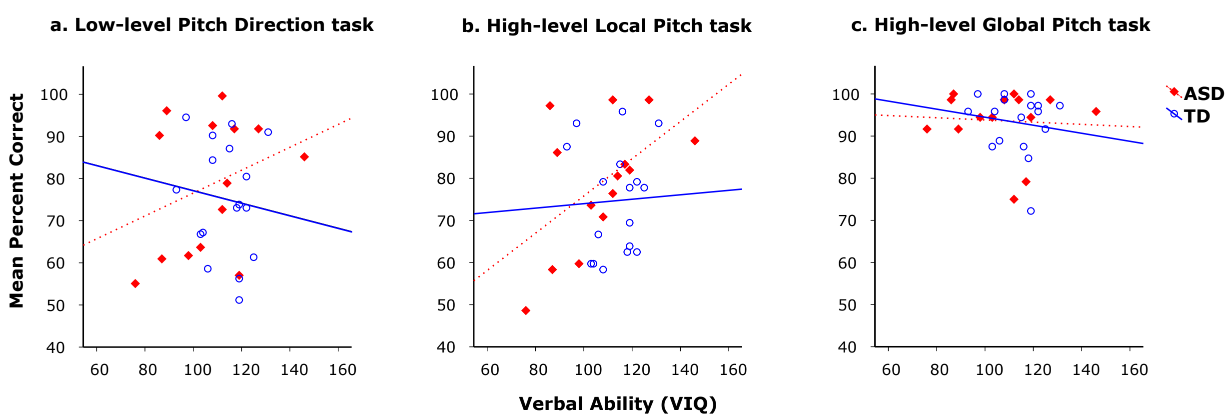

Figure 4: No relation between verbal ability and auditory tasks in ASD or TD. No main effect of verbal ability on performance in ASD and TD or interaction effect between group and VIQ was found on a) the PD task, b) the local GL task, c) the global GL task (all $p > .05$). VIQ: Verbal ability; PD: Pitch Direction; GL: Global-Local

Pitch perception and non-verbal abilities in ASD and TD

The analysis of the relationship between PD performance and NVIQ (Figure 5a) revealed no main effect of group ($F_{(1,27)} = 0.73$, $p = .40$) as well as no interaction effect between group and NVIQ ($F_{(1,27)} < 0.001$, $p > .99$). There was however, a main effect of NVIQ ($F_{(1,27)} = 4.96$, $p = .035$). To further investigate the role of NVIQ on PD, we conducted a post-hoc analysis that showed a trend for a main effect of the Block Design subtest of the NVIQ on PD ($F_{(1,27)} = 5.20$, $p = .062$, Bonferroni corrected) but no main effect of Matrix Reasoning ($F_{(1,27)} = 3.00$, $p = .093$).

For the local condition of the GL task, analyses revealed no main effect of group ($F_{(1,27)} = 1.40$, $p = .25$) as well as no interaction between group and NVIQ ($F_{(1,27)} = 0.82$, $p = .37$). However, there was a main effect of NVIQ ($F_{(1,27)} = 6.61$, $p = .016$; Figure 5b) on GL. To further investigate the role of NVIQ on the local condition of the GL task, we conducted a post-hoc analysis with a Bonferroni correction that showed a main effect of the Block Design subtest of the NVIQ on local pitch perception ($F_{(1,27)}= 8.00$, $p = .018$), but no effect of the Matrix Reasoning ($F_{(1,27)}= 3.29$, $p = .15$) subtest.

For the global condition of the GL task, analyses revealed no main effect of group ($F_{(1,27)}= 0.08$, $p = .78$), as well as no main effect of NVIQ ($F_{(1,27)} = 1.58$, $p = .22$). Furthermore, there was a small interaction effect between group and NVIQ ($F_{(1,27)} = 4.36$, $p = .046$; Figure 5c). However, subsequent within group regression analyses with a Bonferroni correction revealed no significant relationship between NVIQ and global accuracy on the GL task in TD ($r = 0.52$, $p = .07$) or ASD ($r = 0.17$, $p =1.1$) groups.

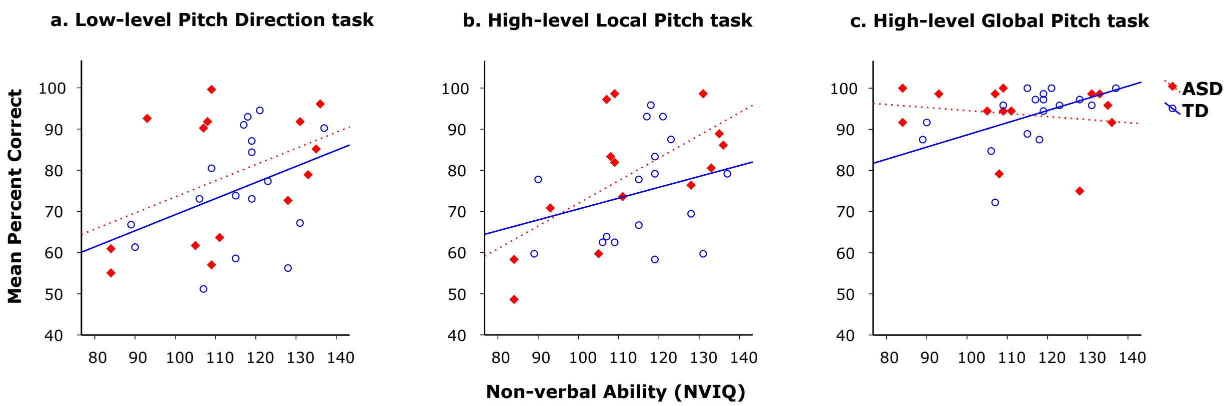

Figure 5: Non-verbal ability predicts performance on auditory tasks in ASD and TD. Non-verbal ability predicted performance a) on PD and b) local GL tasks (all p < .05) for both ASD and TD but not for c) global GL task (p = .22).

NVIQ: Non-verbal ability; PD: Pitch Direction; GL: Global-Local

Discussion

The main objective of this study was to better understand the relationship between auditory pitch perception and verbal and non-verbal cognitive abilities in ASD versus TD children. Two different auditory tasks were used to examine this relationship, a low-level pitch direction (PD) task and a high-level global-local (GL) task. Cognitive abilities were assessed using the verbal and non-verbal IQ subtests of the WASI. No differences in performance were found between the ASD and TD groups on any of the auditory tasks or cognitive measures. Furthermore, there was no effect of verbal intelligence on auditory task performance in either group. However, there was a significant relationship between non-verbal skills and auditory perception in ASD and TD, for both simple and complex auditory tasks. The present findings add to the existing literature on preserved auditory perception in a subsample of school-age age children with ASD without intellectual impairment and support the idea of 'islets of abilities' in ASD. These results also provide motivation to study the role of non-verbal intelligence to explain individual differences in sensory processing in ASD and can lead to a better understanding of perceptual-cognitive phenotypes in ASD.

Intact auditory perception and cognitive abilities in ASD

In the present study, no performance differences were found between ASD and TD on either the low-level PD or high-level GL pitch tasks. These results fit well with previous findings of intact pitch processing in ASD (Foxton et al., 2003; Heaton, 2005), supporting the idea that many children with ASD may have 'islets of ability' or domains of strengths amid their widespread socio-cognitive impairments. However, at the same time, these findings are inconsistent with previously proposed frameworks of perceptual processing in ASD including the Enhanced Perceptual Functioning (EPF) model (Mottron et al, 2006) and the Weak Central Coherence (WCC) theory (Shah and Frith, 1989). The present findings do not support either local-oriented processing or a global processing deficit in ASD relative to TD. The EPF model predicts that individuals with ASD may exhibit superior perceptual performance in tasks involving a simple strategy (such as a low-level pitch discrimination task) and impaired performance in tasks requiring a complex strategy (such as a global-local melodic pitch task) (Mottron et al. 2006). In addition, the EPF model suggests that different patterns of performance in the auditory domain might reflect the idea of a gradient of neural complexity required to process stimuli (Mottron et al., 2006). However, the nature of the auditory tasks used in the present study may not capture the levels of complexity required to show differential processing (i.e. superior featural processing in the low-level PD task or impaired global-local tradeoff in the high-level GL task) in ASD relative to TD (Samson, Mottron, Jemel, Belin, & Ciocca, 2006); however, these tasks do support the idea of spared perception of simple and complex auditory stimuli in higher-functioning children with ASD. While these above frameworks have been very insightful in developing hypotheses about perceptual functioning in ASD, they may not universally explain sensory processing across the autism spectrum. However, building on these theoretical frameworks and applying a developmentally-relevant individual differences approach (i.e. Baum, Stevenson, & Wallace, 2015; Venker, Eernisse, Saffran & Weismer, 2013) might be more informative to understand such perceptual-cognitive phenotypes in a condition as heterogenous as ASD.

Various reasons might explain why no performance differences were found between groups in the present study, as compared to previous reports (e.g. Caron et al., 2006; O'Riordan & Passetti, 2006). These include differences between tasks used across studies, differences in sample characteristics, as well as the heterogeneity of symptomatology in ASD across studies. For example, the present study included a majority of higher-functioning school-age children with ASD with average verbal abilities (VIQ > 70) and no language delay (as measured by the Age of First Word item of the ADI-R). Hence, this particular sample of children with ASD may have a similar verbal intelligence profile to TD children since they did not exhibit the developmental delays in language that are commonly associated with weak verbal ability in children with ASD (Joseph et al. 2002). This signals the need for future research to include participants with lower verbal ability or language delay, in order to more accurately represent the entire range of verbal skills present among individuals with ASD. In light of previous findings, the present results provide evidence of intact low- and higher-level auditory perception in higher-functioning children with ASD. These results also suggest that enhanced auditory abilities might only occur in certain subgroups of individuals with ASD, which signals the importance of studying individual differences in future studies of auditory perception in ASD.

The present findings also do not support previous research showing enhanced performance on the Block Design task in ASD (Caron et al., 2006; Gilchrist et al., 2001; Goldstein et al., 2010; Meilleur et al., 2015; Meilleur et al., 2014; Rumsey & Hamburger, 1988; Shah & Frith, 1993; Siegel et al., 1996; Venter et al., 1992). These results also contradict the WCC framework which suggests that individuals with ASD are likely to demonstrate a preference for local processing when rearranging small parts into a meaningful whole in the context of conflicting global aspects (Shah & Frith, 1993; Mitchell & Ropar., 2004). To elucidate whether most individuals with ASD truly demonstrate superior visuospatial abilities, a recent meta-analysis of 24 studies on the Block Design task revealed that ASD individuals showed enhanced performance in the Block Design task compared to TD controls (Muth, Honekopp, & Falter, 2014). However, this meta-analysis revealed that these previous studies were limited by small effect sizes and substantial unaccounted heterogeneity. Moreover, other work has failed to find enhanced performance on the Block Design task, particularly in individuals with higher-functioning ASD and Asperger's syndrome (Ehlers et al., 1997; Kaland, Mortensen, & Smith, 2007; Mayes & Calhoun, 2003; Ropar & Mitchell, 2001). Some research suggests that outstanding performance on the Block Design task might be observed only in subgroups of individuals with ASD that display superior visuospatial abilities (Caron et al., 2006; Soulières et al., 2011; Stewart, Watson, Allcock, & Yaqoob, 2009). Moreover, it could be argued that locally-oriented processing, which is common in ASD, may be a necessary but not sufficient condition for the development of enhanced performance on the Block Design task in ASD (Caron et al., 2006). This may explain why there is no observed difference in Block Design task performance in the sample of individuals with ASD with moderate to high IQ (ranging 78-146) used in this study. However, an individual differences approach investigating the relation between these various perceptual-cognitive skills is important to provide greater insight on these relationships in ASD.

Pitch perception and verbal abilities in ASD and TD

In this study, no relationship was found between verbal ability and auditory perception in ASD. This might be due to the fact that these participants all belonged to a higher-functioning subset with moderate to high overall verbal IQ (ranging 76-146). Furthermore, a small proportion (3/17) of the current sample had experienced a delayed first word onset (> 24 months, according to ADI criteria). Indeed, in studies where individuals with ASD present a wide range of developmental language delay, larger differences can be observed between groups if they are divided by their age of speech onset, especially in terms of perceptual processing (Barbeau, Dawson, Soulières, Zeffiro, & Mottron, 2013; Bonnel et al., 2010; Jones et al., 2009; Takarae, Luna, Minshew, & Sweeney, 2008). Furthermore, studies comparing language ability to auditory tasks have found evidence of a relationship between enhanced pitch processing and poor language outcomes in ASD (Bonnel et al., 2010; Eigsti & Fein, 2013; Heaton et al., 2008; Jones et al., 2009). Additionally, previous work has found that auditory processing may be enhanced with greater ASD symptom severity (Koldewyn, Jiang, Weigelt, & Kanwisher, 2013) as well as among children with ASD having a history of language delay (Heaton et al., 2008; Jones et al., 2009) compared to children without ASD (Eigsti & Fein, 2013). However, given that the present results are from a sample of school-age children with average and comparable IQ as that of a matched typically developing sample, it is not surprising that we did not find any association between auditory and verbal abilities in this group. Future studies that focus on the use of explicit structural and pragmatic language measures in a more diverse sample may provide further insight on how low-level auditory abilities may be related to higher-order language skills.

Pitch perception and non-verbal abilities in ASD and TD

Here, non-verbal abilities predicted performance on the low-level pitch direction task as well as local pitch processing on the higher-level melodic pitch task for both ASD and TD. However, non-verbal abilities were not associated with global pitch processing in either group.

In the context of the research presented above, our findings of a significant association between non-verbal reasoning and auditory processing abilities suggest that individuals who may have enhanced local processing in the visuospatial domain in terms of the Block Design task also show better performance in auditory pitch processing tasks of different complexities. In addition, this relationship might be similar among school-age children of average intelligence, with or without ASD, for certain low-level auditory tasks requiring a bottom-up processing strategy.

However, very limited research has examined this potential link previously. A possible explanation is that similar perceptual demands are present for the pitch direction as well as the local pitch processing auditory tasks, both of which require more of a bottom-up approach (with or without the global processing trade-off). Interestingly, we also found that ASD and TD participants that performed better on the Block Design task (but not the Matrix Reasoning task) were better able to process local auditory judgment in the context of conflicting global information. As described earlier, the Block Design task requires the construction of a whole starting from disparate parts, and is reliant on effective local perceptual processing abilities and a more bottom-up approach (Shah & Frith, 1993, Caron, 2006). In other words, performance on the Block Design task as well as the local pitch task relies on analyzing stimuli based on their constituent parts (Muth et al., 2014). These findings suggest that a local processing strategy may be engaged across tasks of different perceptual nature by both higher-functioning children with ASD as well as TD children. In other words, the cognitive strategy used for the non-verbal cognitive task may be analogous to the processes used for low- and higher-level auditory tasks across both higher-functioning children with ASD and TD children.

The results of the study, however, do not support an association between non-verbal cognitive abilities and perception of global pitch processing in ASD and TD children. An efficient strategy for the global pitch condition of the high-level auditory task may be accomplished by shifting strategies to a more top-down approach (Foster et al., 2016), contrary to the bottom-up processing requirements of our non-verbal reasoning tasks. A previous study by our research group (Foster et al, 2016) that examined local versus global auditory processing a partially overlapping sample reported that 6 to 18 year olds with ASD, with average IQ, did not show a global-local trade-off as reported previously (Bouvet, Rousset, Valdois & Donnadieu, 2011), thereby supporting the lack of a relationship between the Block Design task and performance on the global condition of the melodic pitch task for both groups. Another potential explanation for this lack of association might be that the cognitive tasks used in this study were not sensitive enough to allow for a global processing advantage. One study used a modified Block Design task developed by Akshoomoff and Stiles (1996) that distinguished global and local patterns in order to most sensitively measure performance differences in block reconstruction and segmentation abilities in higher-functioning individuals with ASD and matched controls (Jonge et al. 2009). They found no differences between both groups in the number of patterns constructed correctly or in reconstruction time. They found, however, that both groups were faster at reconstructing local patterns than global patterns, and that the ASD group made fewer block rotation errors. Findings from this study suggest that overall, higher-functioning individuals with ASD may not employ different cognitive strategies relative to TD, but that they may process stimuli in a more efficient way. Future studies using such fine-tuned cognitive measurements that distinguish global and local patterns may more adequately assess whether non-verbal cognitive abilities are associated with auditory tasks of varying complexities.

Although our findings contradict previous reports of a preference for local processing in ASD (Behrmann et al., 2006; Bertone et al., 2010; Caron et al., 2006; Kellerman et al., 2005;

O'Connor, 2012; Ouimet et al., 2012; Simmons et al., 2009), they fit well with studies that fail to show a local processing advantage in ASD relative to TD (Foxton et al., 2003; Heaton, 2005). They also support accounts of individuals with ASD that do not show a universal global processing deficit (Koldewyn et al., 2013; Mottron et al., 1999, 2003; Wang, Mottron, Peng, Berthiaume, & Dawson, M., 2007). This could be because such enhancements or impairments may only occur in a specific subgroup of children with ASD who demonstrate such a preference for local perception. For instance, a recent study examining the relationship between peak abilities in visual and auditory tasks in ASD reported that the presence of a perceptual peak in a pitch discrimination task was not necessarily associated with enhanced performance in the Block Design task (Meilleur et al., 2015). These peaks were more likely to emerge in individuals with ASD with lower IQ versus those with moderate or higher IQ, which may explain why the current study sample do not exhibit peak performance in the Block Design task. Furthermore, the same study revealed that perceptual peaks in both visual and auditory tasks only co-occurred in about one quarter of participants with ASD. Meilleur and colleagues also observed the prevalence of relative strengths in Block Design task and pitch discrimination in ASD versus TD participants and reported that these strengths existed separately in less than half of the ASD sample.

Indeed, past research has indicated that strengths in low- and higher-level processing may sometimes, but not always go hand in hand, suggesting that individual differences may account, in part, for the variety of processing styles observed across perceptual literature of ASD. Taken together, current findings in combination with existing literature indicate the complexity of perceptual-cognitive relationships in ASD which may best be understood by studying individuals of varying intellectual abilities and varying ages. They also demonstrate the presence of a subgroup of children with ASD who have similar perceptual-cognitive profiles as typically developing children. These findings add to the increasing literature that utilize an individual differences approach (i.e. Baum et al., 2015; Venker et al., 2013) to account for the heterogeneity of ASD. Hence, building on the theoretical frameworks proposed in the past, in addition to considering developmentally-relevant individual differences of the disorder to our advantage rather than as a limitation, may help us understand such perceptual-cognitive phenotypes in a condition as heterogeneous as ASD.

Future directions

The results of this study serve to better characterize perceptual-cognitive phenotypes, in particular, auditory perception in relation to verbal and non-verbal abilities in school-age children of average IQ, diagnosed with ASD. These findings motivate a deeper examination of these relationships in a broader sample of individuals with ASD, including ones with varying age, symptomatology, IQ and language abilities in a larger and more representative sample. The ASD group in the present study consisted of all males. This is a common recruitment challenge in ASD research due to existing research that suggests that an estimated 80% of ASD cases to be males (Werling & Geschwind, 2013), thereby highlighting the importance of testing both males and females with ASD using a larger sample size to see if these results generalize across genders. Accounting for a wider range of ability and functioning within the disorder, particularly in the domains of language and IQ, would allow for a better understanding of the individual differences present in individuals with ASD.

Conclusion

This study provides evidence for a relationship between auditory pitch perception and non-verbal abilities (rather than verbal skills) in ASD and TD. More specifically, non-verbal abilities (especially on the Block Design task) predict better auditory perception in low-level as well as high-level pitch tasks, for ASD and TD similarly. The present findings also provide evidence for preserved auditory perception and cognitive abilities in higher-functioning children with ASD. Findings from this research support the presence of perceptual strengths in subgroups of children with ASD. They also highlight common perceptual-cognitive profiles in these subgroups of children with ASD that are similar to typically developing controls. Deconstructing a condition as heterogeneous as ASD using individual differences across a variety of cognitive and perceptual abilities will likely be critical to better characterize 'islets of ability' in ASD.

GENERAL DISCUSSION

The main objective of my master's thesis was to investigate the association between auditory performance and verbal and non-verbal abilities in ASD versus TD children. Two different auditory tasks of varying complexity were used: a low-level pitch direction task and a high-level global-local task. Cognitive abilities were assessed using the verbal (VIQ) and non-verbal (NVIQ) IQ subscales of the Wechsler Abbreviated Scale of Intelligence (WASI).

Overall, findings revealed that:

1. There were no performance differences between ASD and TD groups on all measures of auditory perception and cognitive abilities. Hence, this particular sample of school-age children of average IQ diagnosed with ASD demonstrated intact auditory abilities based on their performance on low- and higher-level auditory pitch perception tasks, and showed similar verbal and non-verbal cognitive abilities relative to age- and IQ- matched TD children.
2. Verbal abilities did not predict performance on auditory tasks in ASD or TD children.
3. Non-verbal abilities predicted performance on auditory perception in both ASD and TD children. This relationship was particularly strong for the Block Design subtest of the WASI, rather than the non-verbal Matrix Reasoning subtest. Specifically, higher scores on the Block Design task were related to better performance on the low-level pitch direction task as well as in high-level local pitch judgments in both ASD and TD, but were not associated with high-level global pitch judgments in either group.

Contributions of this master's thesis to research in sensory perception and cognitive abilities in ASD

The overall aim of the present research was to better characterize sensory processing in the auditory domain in both ASD and TD, with a special focus on the effects of verbal and non-verbal cognitive abilities. Findings from this study extend previous work on perceptual-cognitive associations in ASD and TD by providing evidence of an association between auditory perception and non-verbal cognitive abilities, rather than verbal abilities. Although this study reveals similar auditory perception and cognitive processing styles across ASD and TD children, it provides a basis for understanding how these two domains are associated using a variety of perceptual tasks and measures. Preserved auditory and cognitive abilities in ASD, in combination with our findings that non-verbal abilities (especially on the Block Design subtest of the WASI) modulated overall auditory perception in both ASD and TD, suggest 1) the potential for a subgroup of school-age children with ASD without intellectual impairment that may show comparable processing styles relative to TD children, and 2) that similar perceptual demands involving local processing may be required for the auditory and non-verbal cognitive tasks used in this study by both ASD and TD groups. Overall, these results motivate further research examining the role of non-verbal intelligence to explain individual differences in sensory processing in ASD, which in turn, can help further refine perceptual-cognitive phenotypes in ASD.

First, our findings of intact auditory processing and cognitive abilities in ASD expand on past reports showing no performance differences between ASD and TD groups across different domains (Foxton et al., 2003; Ehlers et al., 1997; Heaton et al., 2001, Kaland, Mortensen, & Smith, 2007; Mayes & Calhoun, 2003; Ropar & Mitchell, 2001). At the same time, these findings are inconsistent with previously proposed frameworks of perceptual processing in ASD: the Enhanced Perceptual Functioning (EPF) model (Mottron et al, 2006) and the Weak Central Coherence (WCC) theory (Frith, 1989). For instance, our finding of spared perception of simple and complex auditory perception in ASD compared to controls is inconsistent with the EPF model, which emphasizes that low-level perception leads to enhanced local-based processing in ASD (Mottron, 2006). In addition, our finding of intact performance on the Block Design task of the WASI in ASD, does not support the WCC theory, which suggests that individuals with ASD would exhibit enhanced performance relative to TD in tasks involving a local analysis of the stimuli. While these above frameworks have been very insightful in developing hypotheses about perceptual functioning in ASD, they may not universally explain sensory processing across the autism spectrum. Instead, these findings of preserved perceptual and cognitive abilities in ASD provide support for the idea that there may be subgroups within the autism spectrum that have 'islets of ability,' and thereby demonstrate similar perceptual styles to those encountered in typical development. In other words, in a condition as heterogeneous as ASD, some individuals may show strengths in certain domains despite the impairments underlying their diagnosis, which may lead to comparable performance to their typically-developing counterparts. Considered together, the present findings provide the basis for further inspection of whether subgroups of individuals with ASD display divergent styles of processing compared to TD individuals. For instance, previous findings have reported strengths in various sensory modalities (e.g. pitch processing and Block Design task) in individuals with ASD that had a lower IQ compared to those with moderate to higher IQ (Meilleur et al., 2015). Similarly, strengths in sensory perception have also been reported in individuals with ASD with impaired language abilities compared to those without language impairments (Barbeau et al., 2013; Bonnel et al., 2010; Jones et al., 2009; Takarae et al., 2008). In this study, only a small proportion (3/17) of the current ASD demonstrated delayed age of speech onset and displayed moderate to high overall verbal IQ (ranging 76-146), which did not allow to properly investigate whether language impairments modulated cognitive or perceptual abilities in ASD. In sum, the present findings motivate future research using a more diverse sample that includes participants with lower verbal ability as well with delayed or impaired language, to more accurately represent the widespread socio-cognitive impairments present among individuals with ASD. Hence, building on the proposed theoretical frameworks and applying a developmentally-relevant individual differences approach (i.e. Baum, Stevenson, & Wallace, 2015; Venker, Eernisse, Saffran & Weismer, 2013) might be more informative to understand perceptual-cognitive phenotypes in a condition as heterogeneous as ASD.

Second, our findings revealed a significant association between non-verbal reasoning and performance on both the low-level pitch direction and high-level local pitch processing tasks for both ASD and TD. Most strikingly, higher scores on the Block Design cognitive task predicted performance on local auditory judgments across both groups. Although there has been very limited research examining this association in the past, these results imply that similar processing demands may be present across tasks that require shifting to a local strategy in the context of conflicting global information for both higher-functioning children with ASD and TD children. This may also explain why our findings failed to reveal an association between non-verbal reasoning tasks and global pitch judgments across groups, as both tasks may rely on conflicting processing requirements. Although our findings contradict previous reports of a preference for local processing in ASD (Behrmann et al., 2006; Bertone et al., 2010; Caron et al., 2006; Kellerman et al., 2005; O'Connor, 2012; Ouimet, Foster, Tryfon, et al., 2012; Simmons et al., 2009), they fit well with other studies that show no local processing advantage for ASD relative to TD. They also support accounts of individuals with ASD that do not show a universal global processing deficit (Koldewyn et al., 2013; Mottron et al., 1999, 2003; Wang et al., 2007). Taken together, the findings of this study not only builds on previous literature supporting preserved auditory abilities as well as intact cognitive skills in a sample of higher-functioning children with ASD relative to TD children, but they also shed light on the complex processing strategies that underlie perceptual-cognitive relationships in ASD and TD. To better investigate the association between auditory perception and cognitive reasoning in ASD relative to TD, future studies may develop finer-tuned measurements of both cognitive ability (Jonge et al., 2009) and auditory perception in order to assess whether ASD and TD individuals process stimuli in a different way, despite employing similar strategies to accomplish their goals. More importantly, these relationships may be better characterized using an individual differences approach, using a wider variety of symptom-based variability across groups, to better account for the heterogeneity of ASD.

Future directions and implications

The present data contributes to a better understanding of auditory and cognitive perceptual performance in specifically higher-functioning children with ASD. Previous evidence suggests that atypical visual global-local processing, particularly in terms of locally-oriented processing, may increase as a function of symptom severity in ASD (Koldewyn et al., 2013). These relationships underline the crucial importance of taking individual differences in the symptomatology of ASD into consideration in future studies of auditory perception in ASD.

Since music is inherently non-verbal, it provides a unique opportunity to study individuals with ASD who demonstrate atypical language profiles (Ouimet et al., 2012). Hence, a useful extension of the present study would be to include a larger sample size of individuals with varying language abilities and IQ scores, as a way to assess whether new differences could arise depending on symptom severity in ASD. Furthermore, better performance on basic auditory tasks has been reported in individuals with delayed versus typical language onset (Bonnel et al. 2010: Heaton et al, 2008; Jones et al, 2009), suggesting that individuals with delayed speech may also demonstrate a distinct local advantage relative to those with typical speech onset. Hence, future work examining the links between auditory global-local processing, symptom severity, and language impairments may help elucidate individual differences in perception across ASD (Foster et al, 2016), and may result in promising developments of auditory-based interventions in ASD. Given these findings, accounting for the heterogeneous nature of auditory profiles in ASD may also shed light on the potential association between pitch perception and verbal abilities in ASD, especially in the context of processing of social and more complex sounds, such as speech. Moreover, further refining these auditory tasks in order to test children that demonstrate a wider range of ability within the disorder, especially in the domains of language and IQ, might serve to better distinguish the variability of individual differences present in ASD. Finally, future research and clinical work may want to consider longitudinal study designs to contribute to a clearer definition of the developmental trajectory of auditory processing in relation to language and cognitive abilities within individuals with ASD over time.

Concluding remarks

The main goal of this master's thesis was to examine auditory pitch perception across types of cognitive abilities and language ASD and TD populations. The present study supports existing literature linking auditory perception to cognitive abilities, by highlighting a potential association between auditory pitch perception and non-verbal abilities (rather than verbal skills) in ASD and TD. More specifically, better non-verbal abilities (especially on the Block Design task) predict better auditory perception in low-level pitch direction as well as higher-level local pitch judgments tasks, for both ASD and TD. The present findings also provide support for preserved auditory perception and cognitive abilities in higher-functioning school-age children with ASD. These findings expand our knowledge on how sensory perception can vary across different levels of processing, and in turn, encourages future studies to include carefully examined samples of individuals with ASD expressing a wide range of abilities. A challenge often associated with studies of ASD is an overrepresentation of higher-functioning individuals, which may not reflect the heterogeneity present in the autism spectrum as whole. As such, increasing the sample sizes to include a larger variation in the sample by integrating a wide range of language and cognitive abilities will help to better characterize subgroups of individuals with ASD that present 'islets of abilities.' In sum, a deeper comprehension of individual differences in sensory perception in ASD may not only contribute to refine perceptual-cognitive phenotypes in ASD, but may also lead to more targeted interventions.

References

Akshoomoff, N. A., & Stiles, J. (1996). The influence of pattern type on children's block design performance. Journal of the International Neuropsychological Society, 2(05), 392-402.

Alcàntara, J. I., Weisblatt, E. J. L., Moore, B. C. J., & Bolton, P. F. (2004). Speech-in-noise perception in high functioning individuals with autism or Asperger's syndrome. *Journal of Child Psychology and Psychiatry*, *45*(6), 1107–1114.

American Psychiatric Association & American Psychiatric Association. (2000).*Diagnostic and statistical manual of mental disorders: DSM-IV-TR*. Washington, DC: American Psychiatric Association.

American Psychiatric Association & American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders: DSM-5*. Washington, D.C: American Psychiatric Association.

Anderson, D. K., Lord, C., Risi, S., DiLavore, P. S., Shulman, C., Thurm, A., … Pickles, A. (2007). Patterns of growth in verbal abilities among children with autism spectrum disorder. *Journal of Consulting and Clinical Psychology*, *75*(4), 594–604.

Barbeau, E. B., Dawson, M., Soulières, I., Zeffiro, T. A., & Mottron, L. (2013). The Level and Nature of Autistic Intelligence III: Inspection Time. *Journal of Abnormal Psychology*, *122*(1), 295–301.

Baum, S. H., Stevenson, R. A., & Wallace, M. T. (November 01, 2015). Behavioral, perceptual, and neural alterations in sensory and multisensory function in autism spectrum disorder. Progress in Neurobiology, 134, 140-160.

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

Bertone, A., Hanck, J., Kogan, C., Chaudhuri, A., & Cornish, K. (2010). Associating neural alterations and genotype in autism and fragile X syndrome: Incorporating perceptual phenotypes in causal modeling. *Journal of Autism and Developmental Disorders*, *40*(12), 1541–1548.

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.

Black, D. O., Wallace, Æ. G. L., Sokoloff, J. L., & Kenworthy, Æ. L. (2009). Brief Report : IQ Split Predicts Social Symptoms and Communication Abilities in High-Functioning Children with Autism Spectrum Disorders, 1613–1619.

Bonnel, A., McAdams, S., Smith, B., Berthiaume, C., Bertone, A., Ciocca, V., … Mottron, L. (2010). Enhanced pure-tone pitch discrimination among persons with autism but not Asperger syndrome. *Neuropsychologia*, *48*(9), 2465–2475.

Bonnel, A., Mottron, L., Peretz, I., Trudel, M., Gallun, E., & Bonnel, A.-M. (2003). Enhanced pitch sensitivity in individuals with autism: a signal detection analysis. *Journal of Cognitive Neuroscience*, *15*(2), 226–235.

Boucher, J. (2003). Language development in autism. *International Journal of Pediatric Otorhinolaryngology*, *67*(S1), S159–S163.

Bouvet, L., Rousset, S., Valdois, S., & Donnadieu, S. (2011). Global precedence effect in audition and vision: Evidence for similar cognitive styles across modalities. Acta psychologica, 138(2), 329-335.

Bouvet, L., Simard-Meilleur, A. A., Paignon, A., Mottron, L., & Donnadieu, S. (2014). Auditory local bias and reduced global interference in autism. Cognition, 131(3), 367-372.

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

Charman, T., Taylor, E., Drew, A., Cockerill, H., Brown, J. A., & Baird, G. (2005). Outcome at 7 years of children diagnosed with autism at age 2: Predictive validity of assessments conducted at 2 and 3 years of age and pattern of symptom change over time. *Journal of Child Psychology and Psychiatry*, *46*(5), 500–513.

Charman, T., Pickles, A., Simonoff, E., Chandler, S., Loucas, T., & Baird, G. (2011). IQ in children with autism spectrum disorders: data from the Special Needs and Autism Project (SNAP). *Psychological Medicineedicine*, *41*(3), 619–27.

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

Dawson, G., Webb, S. J., & McPartland, J. (2005). Understanding the nature of face processing impairment in autism: insights from behavioral and electrophysiological studies. Developmental neuropsychology, 27(3), 403-424.

DePape, A. M. R., Hall, G. B., Tillmann, B., & Trainor, L. J. (2012). Auditory processing in high-functioning adolescents with autism spectrum disorder. PloS one, 7(9), e44084.

Developmental, D. M. N. S. Y., & 2010 Principal Investigators. (2014). Prevalence of autism spectrum disorder among children aged 8 years-autism and developmental disabilities monitoring network, 11 sites, United States, 2010. Morbidity and mortality weekly report. Surveillance summaries (Washington, DC: 2002), 63(2), 1.Ehlers, S., Nydén, A., Gillberg, C., Sandberg, A. D., Dahlgren, S. O., Hjelmquist, E., & Odén, A. (1997). Asperger syndrome, autism and attention disorders: A comparative study of the cognitive profiles of 120 children. *Journal of Child Psychology and Psychiatry*, *38*(2), 207–217.

Ehlers, S., Nydén, A., Gillberg, C., Sandberg, A. D., Dahlgren, S. O., Hjelmquist, E., & Odén, A. (1997). Asperger syndrome, autism and attention disorders: A comparative study of the cognitive profiles of 120 children. Journal of Child Psychology and Psychiatry, 38(2), 207-217.

Eigsti, I.-M., & Fein, D. a. (2013). More is less: pitch discrimination and language delays in children with optimal outcomes from autism. *Autism Research*, *6*(6), 605–613.

Farley, M. A., McMahon, W. M., Fombonne, E., Jenson, W. R., Miller, J., Gardner, M., … Coon, H. (2009). Twenty-year outcome for individuals with autism and average or near-average cognitive abilities. *Autism Research*, *2*(2), 109–118.

Foster, N. E. V, Ouimet, T., Tryfon, A., Doyle-Thomas, K., Anagnostou, E., & Hyde, K. L. (2016). Effects of Age and Attention on Auditory Global–Local Processing in Children with Autism Spectrum Disorder. *Journal of Autism and Developmental Disorders*, *46*(4), 1–14.

Foxton, J. M., Stewart, M. E., Barnard, L., Rodgers, J., Young, A. H., O'Brien, G., & Griffiths, T. D. (2003). Absence of auditory "global interference" in autism. *Brain*, *126*(12), 2703–2709.

Frith, U. (1989). Autism: Explaining the enigma.

Gilchrist, A., Green, J., Cox, A., Buton, D., Rutter, M., & Le Couteur, A. (2001). Development and current functioning in adolescents with Asperger syndrome: A comparative study. *Journal of Child Psychology and Psychiatry*, *42*(2), 227–240.

Gillberg, C., & Coleman, M. (2000). The biology of the autistic syndromes. Cambridge University Press.

Goldstein, G., Beers, S. R., Siegel, D. J., & Minshew, N. J. (2010). A comparison of WAIS-R profiles in adults with high-functioning autism or differing subtypes of learning disability. *Applied Neuropsychology ISSN:*, *8*(3), 148–154.

Gordon, R. L., Fehd, H. M., & McCandliss, B. D. (2015). Does music training enhance literacy skills? A meta-analysis. *Frontiers in Psychology*, *6*(1777), 1–16.

Gougoux, F., Lepore, F., Lassonde, M., Voss, P., Zatorre, R. J., & Belin, P. (2004). Pitch discrimination in the early blind: People blinded in infancy have sharper listening skills than those who lost their sight later. *Nature*, *430*(6997), 309–310.

Grube, M., Kumar, S., Cooper, F. E., Turton, S., & Griffiths, T. D. (2012). Auditory sequence analysis and phonological skill. Proceedings of the Royal Society of London B: Biological Sciences, 279(1746), 4496-4504.

Heaton, P. (2005). Interval and contour processing in autism. *Journal of Autism and Developmental Disorders*, *35*(6), 787–793.

Heaton, P. F., Hermelin, B., & Pring, L. (1998). Autism and pitch processing: A precursor for savant musical ability? *Music Perception*, *15*(3), 291–305.

Heaton, P., Hudry, K., Ludlow, A., & Hill, E. (2008). Superior discrimination of speech pitch and its relationship to verbal ability in autism spectrum disorders. *Cognitive Neuropsychology*, *25*(6), 771–82.

Heaton, P., Pring, L., & Hermelin, B. (2001). Musical Processing in High Functioning Children with Autism. *Annals of the New York Academy of Sciences*, *930*, 443–44.

Howlin, P., Savage, S., Moss, P., Tempier, A., & Rutter, M. (2014). Cognitive and language skills in adults with autism: a 40-year follow-up. Journal of Child Psychology and Psychiatry, 55(1), 49-58.

Hudry, K., Leadbitter, K., Temple, K., Slonims, V., McConachie, H., Aldred, C., … Charman, T. (2010). Preschoolers with autism show greater impairment in receptive compared with expressive language abilities. *International Journal of Language & Communication Disorders / Royal College of Speech & Language Therapists*, *45*(6), 681–690.

Järvinen-Pasley, A., Wallace, G. L., Ramus, F., Happé, F., & Heaton, P. (2008). Enhanced perceptual processing of speech in autism. Developmental science, 11(1), 109-121.

Jonge, M., Kemner, C., Naber, F., & Engeland, H. (2009). Block design reconstruction skills: not a good candidate for an endophenotypic marker in autism research. European Child & Adolescent Psychiatry, 18, 4, 197-205.

Jones, C. R. G., Happé, F., Baird, G., Simonoff, E., Marsden, A. J. S., Tregay, J., … Charman, T. (2009). Auditory discrimination and auditory sensory behaviours in autism spectrum disorders. *Neuropsychologia*, *47*(13), 2850–2858.

Joseph, R. M., Tager-Flusberg, H., & Lord, C. (2002). Cognitive profiles and social-communicative functioning in children with autism spectrum disorder. *Journal of Child Psychology and Psychiatry*, *6*(43), 807–821.

Kaland, N., Mortensen, E. L., & Smith, L. (2007). Disembedding performance in children and adolescents with Asperger syndrome or high-functioning autism. *Autism: The International Journal of Research & Practice*, *11*(1), 81–92.

Kanner, L. (1943). Autistic Disturbances of Affective Contact. Nervous Child, 2, 217–250.

Kanner, L., Rodriguez, A., & Ashenden, B. (1972). How far can autistic children go in matters of social adaptation?. Journal of Autism and Childhood Schizophrenia, 2(1), 9-33.

Kellerman, G. R., Fan, J., & Gorman, J. M. (2005). Auditory abnormalities in autism: toward functional distinctions among findings. *CNS Spectrums*, *10*(9), 748–756.

Kjelgaard, M. M., & Tager-Flusberg, H. (2001). An Investigation of Language Impairment in Autism: Implications for Genetic Subgroups. *Language and Cognitive Processes*, *16*(2-3), 287–308.

Klinger, L. G., Dawson, G., & Renner, P. (2003). Autistic disorder. Child psychopathology, 2, 409-454.

Koldewyn, K., Jiang, Y. V., Weigelt, S., & Kanwisher, N. (2013). Global/local processing in autism: Not a disability, but a disinclination. *Journal of Autism and Developmental Disorders*, *43*(10), 2329–2340.

Koyama, T., Tachimori, H., Osada, H., Takeda, T., & Kurita, H. (2007). Cognitive and symptom profiles in Asperger's syndrome and high-functioning autism. *Psychiatry and Clinical Neurosciences*, *61*(1), 99–104.

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., & Lecouteur, A. (1994). Autism Diagnostic Interview-Revised: A Revised Version of a Diagnostic Interview for Carers of Individuals with Possible Pervasive Developmental Disorders. *Journal of Autism and Developmental Disorders*, *24*(5), 659–685.

Loui, P., Kroog, K., Zuk, J., Winner, E., & Schlaug, G. (2011). Relating pitch awareness to phonemic awareness in children: Implications for tone-deafness and dyslexia. Frontiers in Psychology, 2(111), 1–5.

Mayer, J. L., Hannent, I., & Heaton, P. F. (2014). Mapping the Developmental Trajectory and Correlates of Enhanced Pitch Perception on Speech Processing in Adults with ASD. *Journal of Autism and Developmental Disorders*, *46*(5), 1562–1573.

Mayes, S. D., & Calhoun, S. L. (2003). Analysis of WISC-III, Stanford-Binet:IV, and academic achievement test scores in children with autism. *Journal of Autism and Developmental Disorders*, *33*(3), 329–341.

McArthur, G. M., & Bishop, D. V. M. (2004). Frequency discrimination deficits in people with specific language impairment: reliability, validity, and linguistic correlates. Journal of Speech, Language, and Hearing Research, 47(3), 527-541.

Meilleur, A. A. S., Jelenic, P., & Mottron, L. (2015). Prevalence of Clinically and Empirically Defined Talents and Strengths in Autism. *Journal of Autism and Developmental Disorders*, *45*(5), 1354–1367.

Meilleur, A.-A. S., Berthiaume, C., Bertone, A., & Mottron, L. (2014). Autism-specific covariation in perceptual performances: “g” or “p” factor? *PloS One*, *9*(8), 1–13.

Mitchell, P., & Ropar, D. (2004). Executive functions and development: Emerging themes. *Infant and Child Development*, *13*(3), 185–198.

Mottron, L., Bouvet, L., Bonnel, A., Samson, F., Burack, J. A., Dawson, M., & Heaton, P. (2013). Veridical mapping in the development of exceptional autistic abilities. Neuroscience & Biobehavioral Reviews, 37(2), 209-228.

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

Mottron, L., Peretz, I., & Ménard, E. (2000). Local and Global Processing of Music in High-functioning Persons with Autism : Beyond Central Coherence ? *Journal of Child Psychology and Psychiatry*, *41*(8), 1057–1065. Muth, A., Honekopp, J., & Falter, C. M. (2014). Visuo-Spatial Performance in Autism: A Meta-analysis. *Journal of Autism and Developmental Disorders*, *44*(12), 3245–3263.

O'Connor, K. (2012). Auditory processing in autism spectrum disorder: a review. Neuroscience and Biobehavioral Reviews, 36(2), 836–54.

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

O'Riordan, M., & Passetti, F. (2006). Discrimination in autism within different sensory modalities. *Journal of Autism and Developmental Disorders*, *36*(5), 665–675.

Ouimet, T., Foster, N. E. V, Tryfon, A., & Hyde, K. L. (2012). Auditory-musical processing in autism spectrum disorders: a review of behavioral and brain imaging studies. *Annals of the New York Academy of Sciences*, *1252*(1), 325–331.

Ouimet, T., Foster, N. E. V., & Hyde, K. L. (2012). Auditory global-local processing: Effects of attention and musical experience. *The Journal of the Acoustical Society of America*, *132*(4), 2536–2544.

Pickles, A., Anderson, D. K., & Lord, C. (2014). Heterogeneity and plasticity in the development of language: A 17-year follow-up of children referred early for possible autism. Journal of Child Psychology and Psychiatry, 55(12), 1354–1362.

Ropar, D., & Mitchell, P. (2001). Susceptibility to illusions and performance on visuospatial tasks in individuals with autism. *Journal of Child Psychology and Psychiatry*, *42*(4), 539–549.

Rumsey, J. M., & Hamburger, S. D. (1988). Neuropsychological findings in high-functioning men with infantile autism, residual state. *Journal of Clinical and Experimental Neuropsychology*, *10*(2), 201–221.

Shah, A., & Frith, U. (1993). Why do autistic children show superior performance in block design tasks? *Journal of Child Psychology and Psychiatry*, *34*(8), 1351–1364.

Samson, F., Mottron, L., Jemel, B., Belin, P., & Ciocca, V. (2006). Can spectro-temporal complexity explain the autistic pattern of performance on auditory tasks? Journal of Autism and Developmental Disorders, 36(January 2006), 65–76.

Schultz, R. T. (2005). Developmental deficits in social perception in autism: the role of the amygdala and fusiform face area. International Journal of Developmental Neuroscience, 23(2), 125-141.

Schreibman, L., Kohlenberg, B. S., & Britten, K. R. (1986). Differential responding to content and intonation components of a complex auditory stimulus by nonverbal and echolalic autistic children. Analysis and Intervention in Developmental Disabilities, 6(1), 109-125.

Siegel, D., Minshew, N., & Goldstein, G. (1996). Wechsler IQ profiles in diagnosis of high-functioning autism. *Journal of Autism and Developmental Disorders*, *26*(4), 389–406.

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.

Soulières, I., Zeffiro, T. A., Girard, M. L., & Mottron, L. (2011). Enhanced mental image mapping in autism. *Neuropsychologia*, *49*(5), 848–857.

Stanutz, S., Wapnick, J., & Burack, J. A. (2014). Pitch discrimination and melodic memory in children with autism spectrum disorders. *Autism: The International Journal of Research and Practice*, *18*(2), 137–147.

Stevenson, R. A., Siemann, J. K., Schneider, B. C., Eberly, H. E., Woynaroski, T. G., Camarata, S. M., & Wallace, M. T. (2014). Multisensory temporal integration in autism spectrum disorders. *The Journal of Neuroscience*, *34*(3), 691–697.

Stewart, M. E., Watson, J., Allcock, A.-J., & Yaqoob, T. (2009). Autistic traits predict performance on the block design. *Autism: The International Journal of Research and Practice*, *13*(2), 133–142.

Takarae, Y., Luna, B., Minshew, N. J., & Sweeney, J. A. (2008). Patterns of visual sensory and sensorimotor abnormalities in autism vary in relation to history of early language delay. *Journal of the International Neuropsychological Society: JINS*, *14*(6), 980–989.

Takeuchi, A. H., & Hulse, S. H. (1993). Absolute pitch. Psychological bulletin, 113(2), 345.

Tomchek, S. D., Huebner, R. A., & Dunn, W. (2014). Patterns of sensory processing in children with an autism spectrum disorder. Research in Autism Spectrum Disorders, 8(9), 1214-1224.

Turner, L. M., Stone, W. L., Pozdol, S. L., & Coonrod, E. E. (2006). Follow-up of children with autism spectrum disorders from age 2 to age 9. *Autism: The International Journal of Research & Practice*, *10*(3), 243–265.

Venker, C. E., Eernisse, E. R., Saffran, J. R., & Weismer, S. E. (2013). Individual differences in the real-time comprehension of children with ASD. Autism Research, 6(5), 417-432.

Venter, A., Lord, C., & Schopler, E. (1992). A follow-up study of high-functioning autistic children. *Journal of Child Psychology and Psychiatry*, *33*(3), 469–597.

Wang, L., Mottron, L., Peng, D., Berthiaume, C., & Dawson, M. (2007). Local bias and local-to-global interference without global deficit: A robust finding in autism under various conditions of attention, exposure time, and visual angle. Cognitive Neuropsychology, 24(5), 550-574.

Wechsler, D. (1999). *Wechsler abbreviated scale of intelligence (WASI)*. Harcourt Assessment: London.

Wechsler, D., & Hsiao-pin, C. (2011). *WASI-II: Wechsler abbreviated scale of intelligence.* Pearson.

Werling, D. M., & Geschwind, D. H. (2013). Sex differences in autism spectrum disorders. *Current Opinion in Neurology*, *26*(2), 146–153.

Zwaigenbaum, L., Scherer, S., Szatmari, P., Fombonne, E., Bryson, S. E., Hyde, K., … Volden, J. (2011). The NeuroDevNet Autism Spectrum Disorders Demonstration Project. *Seminars in Pediatric Neurology*, *18*(1), 40–48.

.