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The Impact of Statistical Learning on Language and Social Competency in ASD and ADHD: Divergent Findings

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Abstract

Statistical learning is a process that allows individuals to extract regularities from the environment and plays an important role in language acquisition, speech segmentation, and aspects of social behaviour. Little is known about the contribution of statistical learning impairments on Autism Spectrum Disorder (ASD) and Attention-Deficit/Hyperactivity Disorder (ADHD) related traits. The current study examined whether impairments in auditory and visual statistical learning are related to ASD and ADHD traits, language, and social competency. Decreased auditory, but not visual statistical learning abilities was related to increased autism traits and visual statistical learning and social competency abilities were mediated by language comprehension. However, no evidence of impaired statistical learning was found in ADHD. Findings highlight the importance of investigating the cascading impact of statistical learning on language and social competency in developmental disorders as well as implementing a more dimensional approach to future studies to capture a broader range of symptoms.

Keywords

Autism Spectrum Disorder, Attention-Deficit/Hyperactivity Disorder, Language, Social Competency, Statistical Learning.

Lay Summary

One way that individuals learn language and social skills is by picking up on patterns that occur in the environment, a process referred to as statistical learning. Once learners understand that some syllables or events occur together more often than others, they can use this information to understand what words mean and how to respond appropriately in social situations. However, individuals with Autism Spectrum Disorder (ASD) and Attention-Deficit/Hyperactivity Disorder (ADHD) traits tend to have difficulties learning these patterns. Our aim was to identify whether statistical learning is related to ASD and ADHD traits and whether impairments in this learning could negatively impact language and social functioning. Such findings could be used to inform intervention programs that include activities that teach pattern learning and have the potential to improve language and social functioning. In turn, individuals who have poor statistical learning abilities can play an active role in improving these skills as they continue to develop.

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List of Abbreviations

Abbreviation	Meaning
$\rho(Y\|X)$	Transitional Probabilities Formula
ASD	Autism Spectrum Disorder
TD	Typically Developing
fMRI	Functional Magnetic Resonance Imaging
RDoC	Research Domain Criteria
Hz	Hertz
F0	Fundamental Frequency
2AFC	Two Alternative Forced Choice
4AFC	Four Alternative Forced Choice
3AFC	Three Alternative Forced Choice
ms	Millisecond(s)
ISI	Interstimulus Interval
CELF	Clinical Evaluation of Language Fundamentals
MSCS	Multidimensional Social Competence Scale
AQ	Autism Quotient
BAPQ	Broad Autism Phenotype Questionnaire
d	Cohens d
t	Student distribution value
p	Probability
r	Correlation coefficient
N	Number of participants
SD	Standard deviation
M	Mean
R^2	Correlation effect size
RDoC	Research Domain Criteria
ab	Indirect effect
c’	C Prime; Direct Effect
c	Total Effect
SE	Standard Error
95%	95% Confidence Interval
z	Z Score
SP	Sensory Profile
ADHD	Attention-deficit/hyperactivity Disorder
SRT	Serial Reaction Time
ASRS	The Adult ADHD Self-Report Scale
Q	Benjamini-Hochberg false discovery rate
BF	Bayesian Factor
F	F distribution value
β	Standardized coefficient
±	Plus or Minus
sr^2	Semi Partial Correlation

Chapter 1

1 Introduction

Our sensory systems are constantly receiving an enormous amount of information from the environment, information that is both continuous and complex. To be able to make sense of this amount of information, we must learn to process sensory inputs in a highly efficient manner. One way to increase efficiency while processing such information involves tracking patterns in the environment to predict what pieces of information follow one another more frequently (Schapiro, Gregory, Landau, McCloskey, & Turk-Browne, 2014). As a result, learners come to understand that information that co-occurs more frequently is more predictable and should be perceptually bound together. This in turn allows the learner to segment continuous pieces of information into discrete, meaningful units, decreasing the overall units of information that need to be processed, and thus allowing them to make better sense of their environment. This process, referred to as statistical learning, functions implicitly, without learners awareness (Arciuli, 2017; Reber, 1967).

While statistical learning increases the efficiency of sensory processing, it also has several important implications for language and social functioning. Early studies examining statistical learning have focused largely on how this ability operates in spoken language (auditory statistical learning; Saffran, Aslin, & Newport, 1996; Saffran, Newport, & Aslin, 1996; Saffran, Newport, Aslin, Tunick, & Barrueco, 1997). While individual words are separated in written language, spoken language is comprised of a continuous stream of auditory information, and it is not always clear when one word ends, and another word begins. Over time, we learn to separate two or more words in speech by tracking how often two or more syllables co-occur together to form meaningful units - syllables that occur together more frequently will be processed as a single unit, whereas syllables that co-occur less frequently will be processed as distinct units.

This process is referred to as stream segmentation (Hayes & Clark, 1970; Saffran et al., 1996) and is perhaps one of the most well-studied areas in statistical learning research. One seminal study in this area presented 8-month old infants with a continuous speech stream during a brief exposure period made up of trisyllabic nonsense words that followed a predictable pattern (Saffran et al., 1996). Following the exposure period, infants were presented with words that appeared in the exposure period as well as novel words, made up of recombined syllables. Results showed that infants were able to learn and remember the groupings of syllables that were highly predictable, as indicated by a preference for the novel words versus those presented during the exposure period.

However, statistical learning is not restricted to the auditory domain. More recent work has shown that learners as young as 2-months old are able to pick up on patterns and reliably segment these patterns in the visual domain as well (Kirkham, Slemmer, & Johnson, 2002). In this study, infants were first presented with a familiarization phase that contained a sequence of shapes that followed a predictable pattern. During the testing phase, they were presented with the same shapes that appeared in the familiarization phase, as well as novel shape sequences that were made up of the same shapes, just rearranged in random order. Learning was measured through looking times with the expectation that infants would fixate longer on the novel shape sequences. Results supported this prediction, showing that infants tended to exhibit longer looking times at the novel, compared to the familiar shape sequences.

Additional work has attempted to examine statistical learning at the neural level using a recently-developed measure of neural entrainment (Batterink & Paller, 2017). Neural entrainment is the brains ability to naturally synchronize with the rhythm of an external source (Batterink & Paller, 2017), such as a repeating pattern of sounds. Brainwave frequencies can then be examined to track the perceptual shift from individual items (syllables), to integrated units (words). Sensory cortices have been shown to initially entrain to the frequency associated with the presentation of individual syllables. For example, consider the syllables *la, tu, go, do, da, bu*. Initially, these syllables would be processed as individual, distinct bits of sensory information. However, as participants come to learn the underlying statistics of the sensory stream, their sensory cortices begin to gradually entrain more strongly at the triplet frequency relative to the individual syllable frequency. In the above example, the individual syllables would then be grouped into trisyllabic 'words' such as, *la tu go, do da bu*. These above findings suggest that not only is statistical learning occurring across multiple modalities, but also that this process is occurring at both behavioral and neural levels.

Given these findings, there has been growing interest in the role that statistical learning plays in early language development. Statistical patterns exist in language and over time, learners become more sensitive to these patterns. There are several aspects of verbal and non-verbal language that can provide probabilistic information such as prosodic cues, immediate social context, stress patterns, and the frequency of co-occurrence (Romberg & Saffran, 2010). Statistical learning is also helpful for understanding higher-order language abilities such as syntax and semantics. For example, probabilistic information can help with learning what word should finish a sentence for it to be considered syntactically correct (Conway, Bauernschmidt, Huang, & Pisoni, 2010) as well as learning associations between words and their appropriate meanings (Ellis, Gonzalez, & Deák, 2014). Statistical learning is therefore an important element in the development of several aspects of language. Interestingly, studies investigating statistical learning in the context of language have demonstrated that auditory and visual statistical learning abilities contribute to different aspects of language where auditory statistical learning appears to be more involved in grammar (Lany, 2014), vocabulary size (Estes, Gluck, & Grimm, 2016), and language processing (Lany, Shoaib, Thompson, & Estes, 2018) and visual statistical learning is more related to syntax (Kidd, 2012; Kidd & Arciuli, 2016), literacy (Arciuli & Simpson, 2012), and receptive language abilities (Ellis et al., 2014).

Although less studied, it has also been suggested that the ability to recognize and apply patterned information is important for certain aspects of social interactions, such as predicting the behavioural patterns of others (Baldwin, Andersson, Saffran, & Meyer, 2008). One can consider how statistical learning may be implicated in social interactions by considering the importance of probabilistic cues during these interactions. First, knowledge of the motions required for a successful social interaction to occur are necessary (e.g. greeting, exchange, goodbye) and with increased experience, learners likely become better at identifying when/what actions signal the beginning and end of an interaction. In turn, this process may help learners better understand how to respond or react appropriately in social interactions. Further, rules that regulate and guide social interactions such as responding appropriately at the right time and standing at a comfortable distance during conversation are often not explicit taught, similar to that of statistical learning in language. Thus, it is possible that statistical learning abilities are helping to guide certain aspects of social behaviour, including recognizing the nuances of body language and engaging in successful social interactions (Baldwin et al., 2008; Jeste et al., 2015; Scott-Van Zeeland et al., 2010).

1.1.1 Statistical Learning in Neurodevelopmental Disorders

In addition to work exploring the manner with which statistical learning relates to language and social processing in typical development, recent work has begun to explore statistical learning in *atypical* development. This work suggests that statistical learning may be impaired in a number of clinical neurodevelopmental disorders, including autism spectrum disorder (ASD) and attention-deficit/hyperactivity disorder (ADHD). How such possible decreases in statistical learning impacts language, social functioning, and clinical traits remains unclear. We and others (Barnes, Howard Jr, Howard, Kenealy, & Vaidya, 2010; Jeste et al., 2015; Klorman et al., 2002; Scott-Van Zeeland et al., 2010) have hypothesized that a decreased ability to pick up on and apply patterned information contribute to ASD and ADHD traits as well as the language and social communication difficulties observed in both groups.

1.1.2 Autism Spectrum Disorder

ASD is a neurodevelopmental disorder associated with social communication difficulties as well as restricted interests and repetitive behaviours (APA, 2013). Among the studies that have explored auditory and visual statistical learning in ASD, findings have been conflicting with some studies reporting impaired learning (Jeste et al., 2015; Jones et al., 2018; Scott-Van Zeeland et al., 2010) and others showing intact or even enhanced learning relative to controls (Brown, Aczel, Jiménez, Kaufman, & Grant, 2010; Haebig, Saffran, & Ellis Weismer, 2017; see Obeid et al. 2016 for a review; Mayo & Eigsti, 2012; Roser, Aslin, McKenzie, Zahra, & Fiser, 2015). In the visual domain, research has demonstrated a link between performance on a statistical learning tasks and autistic participants levels of adaptive social functioning (Jeste et al., 2015) while other research has demonstrated enhanced visual statistical learning in ASD compared to aged-matched controls (Roser et al., 2015). In the auditory domain, one study found links between auditory statistical learning abilities and degree of communication deficits in ASD

(Scott-Van Zeeland et al., 2010) and another study found no difference in performance between individuals with autism compared to controls (Mayo & Eigsti, 2012).

Despite these mixed findings, there is evidence to suggest that impairments in statistical learning may be related to autistic traits. For instance, these individuals tend to focus more heavily on the specific parts of a situation or stimulus rather than considering how smaller details come together to form a whole unit (Frith, 1970;Frith & Happé, 1994; Happé & Frith, 2006), a cognitive-style referred to as weak central coherence. During speech segmentation, it is important for learners to identify what pieces belong together to form meaningful units of information. For instance, individual syllables forming whole words.

As part of the diagnostic criteria, social communication difficulties have been well-documented in the ASD literature (Bishop & Baird, 2001; Geurts & Embrechts, 2008; Geurts, Verté, Oosterlaan, Roeyers, & Sergeant, 2004). Behaviourally, these communication difficulties may manifest as difficulties maintaining eye contact, paying attention, understanding the use of non-verbal language, and little interest engaging others in play. Other social difficulties in ASD include troubles with back and forth conversation, integrating tone and gesture, and deficits in joint attention, all of which have been documented across studies (Charman & Stone, 2008; Qualls & Corbett, 2017; Williams White, Keonig, & Scahill, 2007).

In addition to social communication impairments, several studies have reported impairments related to both the comprehension and production of language in ASD language (Boucher, 2012; Hudry et al., 2014; Hudry et al., 2010), despite not being explicitly part of the diagnostic criteria. Thus, there is evidence to suggest that statistical learning may be impacted by this tendency to default to local, over global processing in ASD and that impairments related to social communication and language may be a result of impaired statistical learning abilities.

1.1.3 Attention-deficit/Hyperactivity Disorder

ADHD is a neurobehavioral disorder characterized by inappropriate degrees of inattention and/or impulsivity/hyperactivity that significantly impact daily functioning (APA, 2013). Statistical learning has been explored in both children and adults with ADHD to test the hypothesis that impairments in statistical learning may contribute to ADHD traits. However, various tasks have been used to examine these potential impairments, making it difficult to generalize and draw strong conclusions from these findings across individuals with ADHD. Among the studies that have examined implicit sequence learning in ADHD, findings have been similar to those found in ASD with some reporting intact (Karatekin, White, & Bingham, 2009; Pedersen & Ohrmann, 2018; Takács et al., 2017; Vloet et al., 2010), and others reporting atypical learning relative to controls (Barnes et al., 2010; Klorman et al., 2002). Similar to ASD, there is evidence to suggest impaired statistical learning in ADHD as these individuals often present with temporal processing deficits and tend to have difficulties organizing information logically (Purvis & Tannock, 1997), both of which are important for segmenting information accurately.

Language and social communication difficulties have also been well-documented in the ADHD literature despite not being core characteristics of the disorder (Geurts & Embrechts, 2008; Gremillion & Martel, 2014; Korrel, Mueller, Silk, Anderson, & Sciberras, 2017; Mueller & Tomblin, 2012; Purvis & Tannock, 1997; Redmond, 2016; Redmond, Ash, & Hogan, 2015) with 40-60% of children with ADHD presenting with comorbid language impairments (Bruce, Thernlund, & Nettelbladt, 2006; Cohen, Davine, Horodezky, Lipsett, & Isaacson, 1993; Hagberg, Miniscalco, & Gillberg, 2010; Oram, Fine, Okamoto, & Tannock, 1999; Sciberras et al., 2014). Social difficulties can present similar in ADHD as in ASD and include poorly organized expressive language, difficulties maintaining eye contact, and excessive talking

(Green, Johnson, & Bretherton, 2014). Impairments in statistical learning may therefore underlie, or further exacerbate issues related to temporal processing, language and social functioning in ADHD.

1.1.4 The Current Study

Given prior work suggesting that (1) statistical learning may be impaired in ASD and ADHD and (2) a number of studies demonstrating that both groups have many comorbid problems related to language and social functioning, it was of interest to examine whether impairments in statistical learning are related to ASD and ADHD traits, language comprehension and production, and social competency skills. Given the discrepancies in findings regarding statistical learning abilities in ASD and ADHD, it is important to examine these abilities to determine whether previous tasks used to measure these abilities fall short in capturing these impairments. Research on statistical learning in ASD and ADHD is limited and among those who have examined these abilities, findings have been mixed. It is therefore crucial to examine whether underlying impairments in statistical learning can help explain the language and social communication difficulties reported in both groups or if there are other mechanisms at play that may explain these reported difficulties.

Study aims were addressed by conducting two separate studies. Overall, we aimed to examine the contribution of auditory and visual statistical learning on traits associated with ASD and ADHD, with three predictions in each. First, we predict that traits related with each disorder will correlate with statistical learning abilities, with a higher level of traits being associated with lower levels of statistical learning. Second, we predict that levels of statistical learning, given that they co-vary with clinical traits, will be associated with language and social abilities, such that higher levels of statistical learning will be accompanied with higher levels of language and social skills. Finally, given these first two relationships hold, we predict that the relationship between statistical learning and social abilities will be mediated by the level of language abilities. In Study 1, we will examine these relationships in ASD and in Study 2, we will extend this work by looking at ADHD.

References

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

Arciuli, J., & Simpson, I. C. (2012). Statistical learning is related to reading ability in children and adults. *Cognitive science*, *36*(2), 286-304. doi: http://dx.doi.org/10.1111/j.1551-6709.2011.01200.x

Baldwin, D., Andersson, A., Saffran, J., & Meyer, M. (2008). Segmenting dynamic human action via statistical structure. *Cognition, 106*(3), 1382-1407. doi: http://dx.doi.org/10.1016/j.cognition.2007.07.005

Barnes, K. A., Howard Jr, J. H., Howard, D. V., Kenealy, L., & Vaidya, C. J. (2010). Two forms of implicit learning in childhood ADHD. *Developmental neuropsychology, 35*(5), 494-505.

Batterink, L. J., & Paller, K. A. (2017). Online neural monitoring of statistical learning. *cortex, 90*, 31-45.

Bishop, D. V., & Baird, G. (2001). Parent and teacher report of pragmatic aspects of communication: use of the Children's Communication Checklist in a clinical setting. *Developmental Medicine and Child Neurology*, *43*(12), 809-818.

Boucher, J. (2012). Research review: structural language in autistic spectrum disorder - characteristics and causes. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *53*(3), 219-233. doi: 10.1111/j.1469-7610.2011.02508.x

Brown, J., Aczel, B., Jiménez, L., Kaufman, S. B., & Grant, K. P. (2010). Intact implicit learning in autism spectrum conditions. *The quarterly journal of experimental psychology, 63*(9), 1789-1812.

Bruce, B., Thernlund, G., & Nettelbladt, U. (2006). ADHD and language impairment. *European child & adolescent psychiatry, 15*(1), 52-60.

Charman, T., & Stone, W. (2008). *Social and communication development in autism spectrum disorders: Early identification, diagnosis, and intervention*: Guilford Press.

Cohen, N. J., Davine, M., Horodezky, N., Lipsett, L., & Isaacson, L. (1993). Unsuspected language impairment in psychiatrically disturbed children: Prevalence and language and behavioral characteristics. *Journal of the American Academy of Child & Adolescent Psychiatry, 32*(3), 595-603.

Conway, C. M., Bauernschmidt, A., Huang, S. S., & Pisoni, D. B. (2010). Implicit statistical learning in language processing: Word predictability is the key. *Cognition, 114*(3), 356-371.

Ellis, E. M., Gonzalez, M. R., & Deák, G. O. (2014). Visual prediction in infancy: What is the association with later vocabulary? *Language Learning and Development, 10*(1), 36-50. doi: http://dx.doi.org/10.1080/15475441.2013.799988

Estes, K. G., Gluck, S. C.-W., & Grimm, K. J. (2016). Finding patterns and learning words: Infant phonotactic knowledge is associated with vocabulary size. *Journal of experimental child psychology, 146*, 34-49.

Frith, U. (1970). Studies in pattern detection in normal and autistic children: II. Reproduction and production of color sequences. *Journal of experimental child psychology, 10*(1), 120-135.

Frith, U., & Happé, F. (1994). Language and communication in autistic disorders. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 346*(1315), 97-104. doi: 10.1098/rstb.1994.0133

Geurts, H. M., & Embrechts, M. (2008). Language profiles in ASD, SLI, and ADHD. *Journal of Autism and Developmental Disorders*, *38*(10), 1931.

Geurts, H. M., Verté, S., Oosterlaan, J., Roeyers, H., & Sergeant, J. A. (2004). How specific are executive functioning deficits in attention deficit hyperactivity disorder and autism? *Journal of Child Psychology and Psychiatry, 45*(4), 836-854. doi: 10.1111/j.1469-7610.2004.00276.x

Green, B. C., Johnson, K. A., & Bretherton, L. (2014). Pragmatic language difficulties in children with hyperactivity and attention problems: An integrated review. *International Journal of Language & Communication Disorders, 49*(1), 15-29. doi: http://dx.doi.org/10.1111/1460-6984.12056

Gremillion, M. L., & Martel, M. M. (2014). Merely misunderstood? Receptive, expressive, and pragmatic language in young children with disruptive behavior disorders. *Journal of Clinical Child and Adolescent Psychology, 43*(5), 765-776. doi: http://dx.doi.org/10.1080/15374416.2013.822306

Haebig, E., Saffran, J. R., & Ellis Weismer, S. (2017). Statistical word learning in children with autism spectrum disorder and specific language impairment. *Journal of Child Psychology and Psychiatry*. doi: http://dx.doi.org/10.1111/jcpp.12734

Hagberg, B. S., Miniscalco, C., & Gillberg, C. (2010). Clinic attenders with autism or attention-deficit/hyperactivity disorder: cognitive profile at school age and its relationship to preschool indicators of language delay. *Research in developmental disabilities, 31*(1), 1-8.

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

Hayes, J. R., & Clark, H. H. (1970). Experiments in the segmentation of an artificial speech analog. *Cognition and the development of language*, 221-234.

Hudry, K., Chandler, S., Bedford, R., Pasco, G., Gliga, T., Elsabbagh, M., . . . Charman, T. (2014). Early language profiles in infants at high-risk for autism spectrum disorders. *Journal of Autism and Developmental Disorders, 44*(1), 154-167. doi: http://dx.doi.org.proxy1.lib.uwo.ca/10.1007/s10803-013-1861-4

Hudry, K., Leadbitter, K., Temple, K., Slonims, V., McConachie, H., Aldred, C., . . . Consortium, P. (2010). Preschoolers with autism show greater impairment in receptive compared with expressive language abilities. *International Journal of Language & Communication Disorders, 45*(6), 681-690. doi: 10.3109/13682820903461493

Jeste, S. S., Kirkham, N., Senturk, D., Hasenstab, K., Sugar, C., Kupelian, C., . . . Johnson, S. P. (2015). Electrophysiological evidence of heterogeneity in visual statistical learning in young children with ASD. *Developmental science, 18*(1), 90-105. doi: 10.1111/desc.12188

Jones, R. M., Tarpey, T., Hamo, A., Carberry, C., Brouwer, G., & Lord, C. (2018). Statistical Learning is Associated with Autism Symptoms and Verbal Abilities in Young Children with Autism. *Journal of Autism and Developmental Disorders*, 1-11.

Karatekin, C., White, T., & Bingham, C. (2009). Incidental and intentional sequence learning in youth-onset psychosis and attention-deficit/hyperactivity disorder (ADHD). *Neuropsychology*, *23*(4), 445.

Kidd, E. (2012). Implicit statistical learning is directly associated with the acquisition of syntax. *Developmental Psychology, 48*(1), 171-184. doi: http://dx.doi.org/10.1037/a0025405

Kidd, E., & Arciuli, J. (2016). Individual differences in statistical learning predict children's comprehension of syntax. *Child development*, *87*(1), 184-193. doi: http://dx.doi.org.proxy1.lib.uwo.ca/10.1111/cdev.12461

Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy: Evidence for a domain general learning mechanism. *Cognition*, *83*(2), B35-B42. doi: http://dx.doi.org/10.1016/S0010-0277(02)00004-5

Klorman, R., Thatcher, J. E., Shaywitz, S. E., Fletcher, J. M., Marchione, K. E., Holahan, J. M., . . . Shaywitz, B. A. (2002). Effects of event probability and sequence on children with attention-deficit/hyperactivity, reading, and math disorder. *Biological Psychiatry*, *52*(8), 795-804.

Korrel, H., Mueller, K. L., Silk, T., Anderson, V., & Sciberras, E. (2017). Research Review: Language problems in children with Attention-Deficit Hyperactivity Disorder—A systematic meta-analytic review. *Journal of Child Psychology and Psychiatry*, *58*(6), 640-654. doi: http://dx.doi.org/10.1111/jcpp.12688

Lany, J. (2014). Judging words by their covers and the company they keep: probabilistic cues support word learning. *Child development*, *85*(4), 1727-1739.

Lany, J., Shoaib, A., Thompson, A., & Estes, K. G. (2018). Infant statistical-learning ability is related to real-time language processing. *Journal of child language*, *45*(2), 368-391.

Mayo, J., & Eigsti, I.-M. (2012). Brief report: A comparison of statistical learning in school-aged children with high functioning autism and typically developing peers. *Journal of Autism and Developmental Disorders*, *42*(11), 2476-2485. doi: http://dx.doi.org/10.1007/s10803-012-1493-0

Mueller, K. L., & Tomblin, J. B. (2012). Examining the comorbidity of language disorders and ADHD. *Topics in Language Disorders*, *32*(3), 228.

Oram, J., Fine, J., Okamoto, C., & Tannock, R. (1999). Assessing the language of children with attention deficit hyperactivity disorder. *American Journal of Speech-Language Pathology, 8*(1), 72-80.

Pedersen, A., & Ohrmann, P. (2018). Impaired behavioral inhibition in implicit sequence learning in adult ADHD. *Journal of attention disorders, 22*(3), 250-260.

Purvis, K. L., & Tannock, R. (1997). Language abilities in children with attention deficit hyperactivity disorder, reading disabilities, and normal controls. *Journal of Abnormal Child Psychology, 25*(2), 133-144. doi: http://dx.doi.org/10.1023/A:1025731529006

Qualls, L. R., & Corbett, B. A. (2017). Examining the relationship between social communication on the ADOS and real-world reciprocal social communication in children with ASD. *Research in Autism Spectrum Disorders, 33,* 1-9. doi: https://doi.org/10.1016/j.rasd.2016.10.003

Redmond, S. M. (2016). Language impairment in the attention-deficit/hyperactivity disorder context. *Journal of Speech, Language, and Hearing Research, 59*(1), 133-142.

Redmond, S. M., Ash, A. C., & Hogan, T. P. (2015). Consequences of co-occurring attention-deficit/hyperactivity disorder on children's language impairments. *Language, Speech, and Hearing Services in Schools*, *46*(2), 68-80.

Romberg, A., & Saffran, J. (2010). Statistical learning and language acquisition. *WIREs Cognitive Science, 1*(6), 906-914. doi: http://dx.doi.org/10.1002/wcs.78

Roser, M. E., Aslin, R. N., McKenzie, R., Zahra, D., & Fiser, J. (2015). Enhanced visual statistical learning in adults with autism. *Neuropsychology, 29*(2), 163-172. doi: http://dx.doi.org.proxy1.lib.uwo.ca/10.1037/neu0000137

Saffran, Aslin, & Newport. (1996). Statistical learning by 8-month-old infants. *Science, 274*(5294), 1926-1928.

Saffran, Newport, & Aslin. (1996). Word segmentation: The role of distributional cues. *Journal of Memory and Language, 35*(4), 606-621.

Saffran, J. R., Newport, E. L., Aslin, R. N., Tunick, R. A., & Barrueco, S. (1997). Incidental language learning: Listening (and learning) out of the corner of your ear. *Psychological Science, 8*(2), 101-105. doi: http://dx.doi.org/10.1111/j.1467-9280.1997.tb00690.x

Schapiro, A. C., Gregory, E., Landau, B., McCloskey, M., & Turk-Browne, N. B. (2014). The necessity of the medial temporal lobe for statistical learning. *Journal of Cognitive Neuroscience, 26*(8), 1736-1747. doi: http://dx.doi.org/10.1162/jocn_a_00578

Sciberras, E., Mueller, K. L., Efron, D., Bisset, M., Anderson, V., Schilpzand, E. J., . . . Nicholson, J. M. (2014). Language problems in children with ADHD: A community-based study. *Pediatrics*, peds. 2013-3355.

Scott-Van Zeeland, A. A., McNealy, K., Wang, A. T., Sigman, M., Bookheimer, S. Y., & Dapretto, M. (2010). No Neural Evidence of Statistical Learning During Exposure to Artificial Languages in Children with Autism Spectrum Disorders. *Biological Psychiatry, 68*(4), 345-351. doi: 10.1016/j.biopsych.2010.01.011

Takács, Á., Shilon, Y., Janacsek, K., Kóbor, A., Tremblay, A., Németh, D., & Ullman, M. T. (2017). Procedural learning in Tourette syndrome, ADHD, and comorbid Tourette-

ADHD: Evidence from a probabilistic sequence learning task. *Brain and Cognition, 117*, 33-40. doi: http://dx.doi.org/10.1016/j.bandc.2017.06.009

Vloet, T. D., Marx, I., Kahraman-Lanzerath, B., Zepf, F. D., Herpertz-Dahlmann, B., & Konrad, K. (2010). Neurocognitive performance in children with ADHD and OCD. *Journal of Abnormal Child Psychology, 38*(7), 961-969.

Williams White, S., Keonig, K., & Scahill, L. (2007). Social Skills Development in Children with Autism Spectrum Disorders: A Review of the Intervention Research. *Journal of Autism and Developmental Disorders, 37*(10), 1858-1868. doi: 10.1007/s10803-006-0320-x

Chapter 2

2 Experiment I – Statistical Learning and Social Competency: The Mediating Role of Language

Over time, we learn which pieces of information belong together or follow one another more frequently and are then able to identify these relationships by uncovering the probabilistic information occurring within them (Schapiro, Gregory, Landau, McCloskey, & Turk-Browne, 2014). This process, known as statistical learning, functions implicitly (Arciuli, 2017; Reber, 1967) and allows individuals to track patterns and probabilities within the environment, and to predict what pieces of information will come next (Cleeremans & McClelland, 1991; Elman, 1990, 1991). Such probabilistic information permeates much of the social world, from recognizing the nuances of body language, to learning associations between words and their appropriate meanings, to social turn taking in a conversation. The ability to discover these underlying regularities helps learners make sense of their world by finding structure in a rapidly changing, continuous environment.

Statistical learning is important for understanding patterns in social interactions (Baldwin, Andersson, Saffran, & Meyer, 2008; Jeste et al., 2015; Scott-Van Zeeland et al., 2010), including how to respond to social events and/or how to adjust one's behaviour accordingly. It also plays an important role in facilitating language skills including syntax (Gómez, 2002) semantics (Graf Estes, Evans, Alibali, & Saffran, 2007), word segmentation (e.g. Saffran, Newport, & Aslin, 1996), and early literacy skills (Arciuli & Simpson, 2012). For example, in English, appropriate syntactic structure can be signaled by highly probable cues such as the word *the* being followed by a noun. Another example is spoken sentences that have highly predictable and non-predictable endings such as the predictable ending *prize* in *her entry should*

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win first prize and the non-predictable ending *beach* in *the arm is riding on the beach* (Conway, Bauernschmidt, Huang, & Pisoni, 2010). Knowledge of such probabilities in spoken language can help a listener identify or predict the next word in a sentence. This probabilistic structure can also help learners recognize syntactic violations as well as better understand word meanings and appropriate sentence structure.

Perhaps the most studied area of statistical learning is in spoken language. Certain syllable pairs occur more often in English (and in other languages as well) but, unlike written words, it is not always clear when one-word ends, and another begins in spoken language. A classic example of this is the phrase *pretty baby.* In natural speech, there is no clear pause between these words. However, over time, we learn to perceptually separate these words, a process known as stream segmentation. One reliable way to segment words is to use a clustering mechanism based on the conditional probabilities between syllables (Hayes & Clark, 1970), or tracking the co-occurrence frequency between syllables. In other words, learners can segment words by uncovering and predicting the statistical patterns that occur between syllables. Statistical regularities are present in words within natural languages, making certain syllables more predictive than others, helping learners determine when one-word ends, and another begins. In turn, this probabilistic information about appropriate language structure can help language learners understand words, word meanings, and sentence structure better (Romberg & Saffran, 2010). Syllables within the same word typically have higher conditional probabilities; they tend to co-occur more often than syllables that occur between words. This high and low probability of co-occurrence can be formally described as the probability of *Y* given *X* (Miller & Selfridge, 1950):

$$p(Y|X) = \frac{p(X \cap Y)}{p(X)}$$

Although this process may seem computationally demanding, research has shown that language learners can use transitional probabilities to reliably segment words from fluent speech (Aslin, Saffran, & Newport, 1998; Saffran, Aslin, & Newport, 1996; Saffran, Aslin, & Newport, 1996). Previous research has demonstrated that even infants can segment words from fluent speech using only transitional probabilities (Saffran et al., 1996) and this finding has been widely replicated in more recent studies using both artificial (Aslin et al., 1998; Batterink, Reber, Neville, & Paller, 2015; Bogaerts, Siegelman, & Frost, 2016; Evans, Saffran, & Robe-Torres, 2009; Misyak & Christiansen, 2012; Siegelman, Bogaerts, & Frost, 2016) and natural languages (Hay, Pelucchi, Estes, & Saffran, 2011; Pelucchi, Hay, & Saffran, 2009).

Although the majority of statistical learning studies have been conducted in the auditory domain, statistical learning is not limited to this modality. The need to segment information into meaningful patterns extends to the visual domain as well (Schapiro & Turk-Browne, 2015). One of the first studies to examine whether statistical learning can operate in the visual domain found that infants as young as 2-months old were able to extract the statistical patterns in a sequence of visually presented shapes (Kirkham, Slemmer, & Johnson, 2002). These findings, along with other research showing that infants and adults are able to learn statistical patterns presented in tone sequences (Creel, Newport, & Aslin, 2004; Saffran, Johnson, Aslin, & Newport, 1999) indicate that statistical learning is a domain-general learning mechanism whereby learners are able to use transitional probabilities to segment sequences across multiple sensory modalities.

Following these findings that statistical learning occurs in infant learners as young as 2-months old, much subsequent attention has been given to the role that it plays in early language

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learning. A longitudinal study examining the relationship between early speech segmentation skills (between age 7 and 12 months) and later vocabulary outcomes found that infants with poor vocabulary skills at age two were less successful at segmenting the speech stream during infancy. Early segmentation ability was significantly related to children's semantic and syntax abilities in the preschool years (Newman, Ratner, Jusczyk, Jusczyk, & Dow, 2006). Further, visual statistical learning has been implicated for its role in language proficiency skills including syntax (Kidd, 2012; Kidd & Arciuli, 2016), early literacy skills (Arciuli & Simpson, 2012), and receptive language ability (Ellis, Gonzalez, & Deák, 2014) while auditory statistical learning is involved in grammar (Lany, 2014), language processing (Lany, Shoaib, Thompson, & Estes, 2018), and vocabulary size (Estes, Gluck, & Grimm, 2016). In particular, research investigating the link between visual statistical learning and language has found that children who show stronger visual statistical learning abilities are better able to detect and adhere to rule changes in syntactic structure (Kidd, 2012). Therefore, it appears that children who are better at identifying patterns and regularities are also better able to apply these patterns to other areas of language, in this case, sentence structure.

Though not as thoroughly studied, emerging research has suggested that statistical learning may play a role in some aspects of reciprocal social interactions, including predicting behavioural patterns (Baldwin et al., 2008). A stronger ability to analyze and predict the current and future actions of others have been hypothesized to lead to more effective social interactions. It may also be that statistical learning helps learners determine how they should respond or react to another individual or during a social event. For instance, it has been suggested that those better at detecting behavioural patterns or relationships are also better able to correlate these relationships with the goals and/or intentions of another individual, helping them to respond

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accordingly. Indeed, past research has demonstrated that adults can successfully uncover statistical regularities that provide information about intentionality in human action (Baldwin et al., 2008) and that auditory and visual processing is related to non-verbal communication in typically developing (TD) and Autism Spectrum Disorder (ASD) children (Noel, De Niear, Stevenson, Alais, & Wallace, 2017). Additionally, research interested in the sequential patterns that occur within social play has shown that children tend to follow normative play patterns during group interactions and that these patterns are stable across gender and socioeconomic status (Robinson, Anderson, Porter, Hart, & Wouden-Miller, 2003). While it is thus apparent that children are acquiring the skills necessary to recognize and apply patterned information to their social world which are crucial to engage in appropriate social interactions, the role that statistical learning plays in this process, and how it relates to competency in social interactions, has not been directly tested. It is therefore important to investigate the potential relationship between statistical learning and social competency to mitigate the amount of social-infringing behaviours that may be a result of an impaired ability to learn patterns and probabilities that guide successful social interactions.

Evidence has also begun to emerge exploring the converse of this relationship - that a decreased ability to learn patterns or relationships that would otherwise enhance language learning could result in social competency deficits. One such empirical testbed for this idea is ASD. ASD is a neurodevelopmental disorder associated with social communication difficulties (APA, 2013). Social communication issues in autism can include difficulties with turn taking during conversation, maintaining eye contact, and understanding the use of non-verbal language. Although not explicitly part of the diagnostic criteria, research has consistently shown that autistic individuals also show impairments related to both the comprehension and production of

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language (Boucher, 2012; Hudry et al., 2014; Hudry et al., 2010; Noel et al., 2017; Stevenson, Baum, et al., 2017). To date, studies that have explored auditory and visual statistical learning in ASD have been mixed with some studies showing impaired learning (Jeste et al., 2015; Jones et al., 2018; Scott-Van Zeeland et al., 2010) and others showing intact learning relative to age-matched controls (Brown, Aczel, Jiménez, Kaufman, & Grant, 2010; Haebig, Saffran, & Ellis Weismer, 2017; see Obeid et al. 2016 for a review ; Mayo & Eigsti, 2012; Roser, Aslin, McKenzie, Zahra, & Fiser, 2015). In the visual domain, research has demonstrated that after a learning phase, autistic individuals showed atypical electrophysiological markers of visual statistical learning relative to TD controls (Jeste et al., 2015), and this index of statistical learning in the autistic participants significantly correlated with their levels of adaptive social functioning. Conversely, other research examining visual statistical learning has found that adults with autism demonstrated enhanced visual statistical learning abilities when compared to age-matched controls (Roser et al., 2015). In the auditory domain, one study did not find differential behavioural statistical learning abilities in autistic individuals relative to controls and additionally failed to find an association between statistical learning and language in the autism group (Mayo & Eigsti, 2012). With that said, it should be noted that the study was relatively underpowered for a correlational analysis (n = 17, largest OP = 0.19). In contrast, another study exploring statistical learning in the auditory domain using functional magnetic resonance imaging (fMRI) found that autistic individuals show decreased responses in the basal ganglia and left supramarginal gyrus during a sequential statistical learning task when compared to TD controls, decreases which correlated with the degree of communication deficits in those with ASD (Scott-Van Zeeland et al., 2010).

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Autistic individuals also have been described as having weak central coherence (Frith, 1989; Frith & Happé, 1994; Happé & Frith, 2006) or a more 'detail-focused' cognitive style where they tend to adopt a domain-general processing style by focusing on the fine details or specific parts of a situation (here being individual syllables) rather than the 'bigger picture' (here being tri-syllabic pseudowords) (Happé & Frith, 2006; Stevenson, Toulmin, et al., 2017). The idea of weak central coherence as a default cognitive style in autism (Frith, 1989) suggests that when left uninstructed, individuals with autism tend to default towards focusing on details or notice features about objects or situations that others may find insignificant. However, the idea of weak central coherence as a cognitive style also suggests that individuals with autism can in fact process at the global level when instructed to do so. Therefore, in tasks that require individuals with autism to ignore meaning or the 'bigger picture' and focus on details or finer parts, weak central coherence will result in superior performance (Stevenson et al., 2016). Conversely, in tasks that require these individuals to extract smaller pieces of information and process that as a whole, meaningful unit, weak central coherence will result in impaired performance (Plaisted, 2015). These clinical findings and theory of weak central coherence provide some converging evidence towards the hypothesis that statistical learning abilities may be impaired in autistic individuals and relate to their social skills, but to date have been equivocal.

Despite past research demonstrating a clear link between statistical learning and language, no studies to date have attempted to understand the contribution of both auditory and visual statistical learning on language and social competency skills which is surprising given that auditory and visual processing are among the most commonly studied modalities in both autism and statistical learning research. Further, while it is predicted that statistical learning would be related to both language and social competencies, it is an open question as to the directionality of this relationship. That is, it is unclear whether statistical learning directly impacts both language and social competency or if statistical learning impacts language abilities, which then in turn affect social competencies.

We aimed to address these open questions in the field with our current study. First, we explored whether a decreased ability to learn auditory and visual statistics are related to receptive language abilities by administering well-established auditory and visual sequence learning paradigms (henceforth referred to as simply *auditory statistical learning* and *visual statistical learning*, respectively) paired with a clinically valid measure of receptive language. Our *a priori* prediction was that auditory and visual statistical learning abilities would be directly related to receptive language abilities. Next, we examined whether statistical learning abilities were related to social competency skills by administering a clinically-validated measure of social competency with the *a priori* prediction that statistical learning abilities would also be directly related to social competency. Importantly, we aimed to examine the directional three-way relationship between statistical learning, language, and social abilities, if applicable. We were interested in how the ability to learn patterns overall is related to language and social competency skills rather than the domain in which the learning occurs. We therefore expected that auditory and visual statistical learning would contribute similarly to participants language and social competency skills given that both tasks assess the ability to learn statistical patterns in general which is thought to be important for successful language and social competency skills. Further, our predictions stemmed from statistical learning in both auditory and visual domains outward to areas related to language and social functioning. Our expectation then, was that impaired statistical learning would have cascading effects on language and social skills.

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Finally, given the previously found impairments in all three of these abilities in ASD, we assessed whether statistical learning abilities in the auditory and visual domains were related to autistic traits, with the *a priori* prediction that individuals with higher levels of autistic traits would show lower levels of statistical learning. We also aimed to explore possible three-way relationships between statistical learning, autistic traits, and language if applicable based on our findings. To achieve good statistical power for detecting relationships between these variables, we took advantage of the fact that, as a spectrum disorder, traits associated with ASD are not confined to clinical populations but are observed at non-clinical levels in the general population. Indeed, several measures have been used to examine the way autistic traits present in the general population, including the Autism Quotient (AQ; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001), and the Broad Autism Phenotype Questionnaire (BAPQ; Hurley, Losh, Parlier, Reznick, & Piven, 2007), which have shown to generalize experimental findings in TD to similar findings in ASD populations (Bölte, Westerwald, Holtmann, Freitag, & Poustka, 2011; Chandler et al., 2007; Constantino et al., 2003; Stevenson et al., 2016).

2.1 Methods

2.1.1 Participants

Prior to exclusion, the initial sample consisted of 104 adults recruited from the undergraduate psychology pool at the University of Western Ontario as part of a larger study (Parks & Stevenson, 2018) who received course credit for study completion. Here, we use the research domain criteria (RDoC) framework with the aim of assessing the entire spectrum of levels of ASD that range from clinical disorders to issues at sub-clinical levels. The RDoC framework allows researchers to incorporate different ways of assessing mental disorders through use of genetics, cognitive science, and neuroimaging techniques (Cuthbert, 2014; Insel

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et al., 2010). Participants were therefore recruited using the RDoC framework and were not required to have a formal ASD diagnosis. The final sample consisted of 95 undergraduate students between 16 to 21 years of age (*Mean age* = 18.18, *SD* = .73, *Median age* = 18, *Interquartile range* = 16), 61 (64.2%) participants being female (see *Analysis* for exclusionary criteria). All participants were English speakers who had normal or corrected-to-normal hearing and vision. Ethics approval for all study procedures and materials was obtained by the University of Western Ontario Non-Medical Research Ethics Board. All methods were performed in accordance with the relevant guidelines and regulations and written informed consent was obtained from all study participants.

2.1.2 Materials and Procedure

Participants were tested individually in a quiet computer testing room seated approximately 60cm away from a computer monitor. Participants first completed well-established auditory and visual statistical learning tasks, followed by a clinical language assessment, a questionnaire measure of social competency, and autistic traits questionnaires.

The statistical language learning task was based on that from Saffran et al. (1997) in order to make current findings comparable to previously conducted studies. Participants first completed a language exposure phase. In the language exposure phase, participants were exposed to a structured, unsegmented language stream for 21 minutes. The language consisted of six tri-syllabic nonsense “words”: *tutibu, babupu, bupada, pidadi, patubi, and dutaba.* There were no acoustic markers to indicate word boundaries between words. However, within the language stream, there were higher transitional probabilities within words (1.0 or 0.33) than between words (0.1 or 0.2).

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The language stimuli were constructed from audio recordings of a female native-English speaker using a neutral vocal effort. Recordings were made in a double-walled IAC sound booth with a pedestal microphone (AKG C 4000B) located approximately 30cm from the speaker's mouth and routed to a USBPre 2 pre-amplifier (Sound Devices) using SpectraPlus software (Pioneer Hill Software, 2008). Recordings were made of each of the 12 target syllables in the middle of a three-syllable sequence, within every coarticulation context required for the language. Eight repetitions of each sequence were recorded, and the token with the most neutral pitch contour and best sound quality was chosen and uploaded into Sound Forge Audio Studio (Sony Creative Software, *version* 10.0) editing software. Middle syllables from the recorded tokens were extracted by identifying the final offset of vowel oscillation in the previous syllable to the offset of vowel oscillation in the target syllable. These were then concatenated to create the final 21-minute stream of words. The stream consisted of 360 tokens of each word in random order, with no word presented twice in sequence. The language maintained a consistent speech rate (average 5.1 syllables/s) using a time stretch and was normalized to a pitch of F0 = 196 Hz using the pitch shift in Sound Forge Audio Studio. There were no pauses between words; as such, the only cues to word boundaries were the lower transitional probabilities for between-word syllable pairs. Language stimuli were presented using E-Prime 2.0.10 (Schneider, Eschman, & Zuccolotto, 2002) through speakers or headphones at a comfortable listening volume.

Immediately following the artificial language exposure, participants completed a two-alternative forced-choice test (2AFC) to assess whether they could identify trained words from the artificial language. For each test item, participants heard a trained word from the artificial language paired with a nonword foil, separated by 500ms of silence. Nonword foils were constructed from the same syllable inventory as the words from the artificial language, with the constrained that the transitional probabilities between syllables were 0.0: *pubati, tapudi, dupitu, tipabu, bidata, batipi*. The foil words were recorded in the same manner as the trained words. Each of the six trained words was paired exhaustively with each of the six foil words, comprising 36 total test items. For the 2AFC test, instructions were displayed on the computer screen, asking participants *'which of these two words sounds most like something you heard in the language'*. Participants indicated their response on a keyboard by pressing the "*A*" or "*L*" key for the first or second "word", respectively. Test instructions remained on the screen throughout the test phase. Correct responses were counterbalanced and equally presented in the first or second presentation to avoid response bias. Overall accuracy on the 2AFC were analyzed.

Next, participants completed the visual statistical learning task, which was identical to the established paradigm used by Siegelman, Bogaerts and Frost (2016) in order to make current findings comparable to previously conducted studies. During this task, participants were seated in front of a computer screen, while novel shapes were presented one at a time **(Figure 1).** As with the artificial language stimuli, the shapes were presented in a structured, unsegmented sequence. The shapes were organized into eight triplets that differed according to their within-triplet transitional probabilities, with four triplet items having transitional probabilities of .33 and the other four having transitional probabilities of 1.0. Between-triplet transitional probabilities were .14 or less **(Figure 2).** Participants passively viewed the stream of shapes for 10 minutes, with each triplet sequence appearing 24 times. Shapes were presented for 800ms, with a 200ms inter-stimulus interval (ISI).

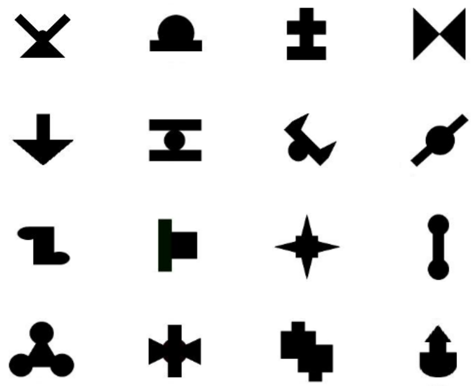

Figure 1: 16 novel shapes used in visual paradigm.

The test phase began immediately following the learning phase. The test phase used in the current study was identical to that used by Siegelman et al. (2016), and consisted of 42 test items of varying difficulty, presented one at a time. This task differed from previous statistical learning tasks in that test items required different responses as well as differed from one another in terms of item difficulty and the number of response options. The first block of 34 trials were pattern recognition items, and required participants to pick the familiar, or trained, sequence from either two (2AFC) or four (4AFC) possible responses. Pattern recognition items included both pairs of shapes (part triplets) and triplets. For the 24-items that contained triplet sequences, participants were instructed to *'choose the pattern that appeared together in the first part'*, sixteen being 2AFC and eight 4AFC. For the ten items that contained pairs of shapes participants were instructed to *'choose the pattern that you are most familiar with as a whole'*, six being 2AFC and four 4AFC. Instructions on recognition items therefore differed depending on whether the participant was presented with triplet or part triplet sequences. All responses were numbered, and participants indicated their response by clicking the corresponding key on a keyboard. The

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next eight trials were pattern completion items. For these trials, participants were shown an incomplete trained sequence, and selected the shape that best completed the sequence from a set of three possible responses. Participants were instructed to *'choose the shape that best completes the pattern'* from the 3AFC items, which included four triplet-completion items and four pair-completion (that is, part-triplet) items. For all test trials, there was only one triplet or part-triplet that followed the statistical regularities presented in the test phase. Accuracy scores were collected and analyzed for all items.

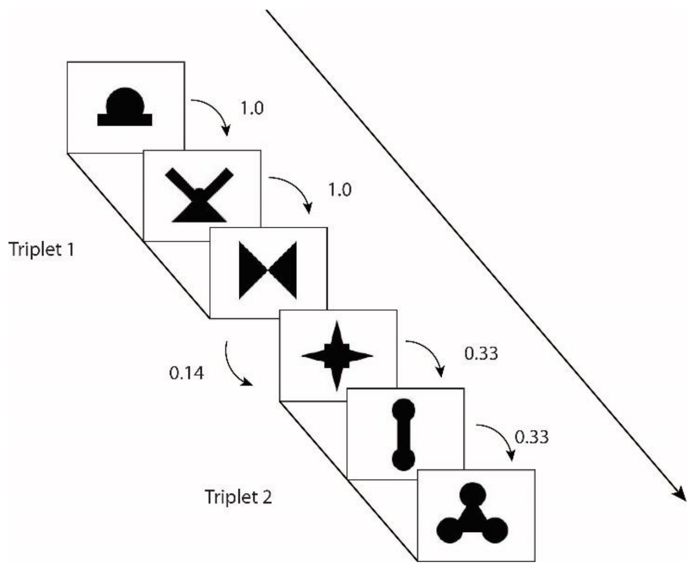

Figure 2: Example of probabilities within and between triplets.

Participants receptive and expressive language abilities were examined by administering six subtests from the *Clinical Evaluation of Language Fundamentals* (CELF-5; Wiig, Semel, Secord, & Pearson Education, 2013), with our focus being on receptive language. The CELF-5 is a commonly used language measure that is sensitive to receptive and expressive language abilities of child and adult clinical populations including specific language impairments (Conti-Ramsden, 2003), attention deficit hyperactivity disorder (Oram, Fine, Okamoto, & Tannock, 1999), and ASD (Kjelgaard & Tager-Flusberg, 2001). Three subtests were administered to examine receptive language abilities and included *Word Classes*, *Understanding Spoken Paragraphs*, and *Semantic Relationships* and three subtests examined expressive language abilities, and included *Formulating Sentences*, *Recalling Sentences*, and *Sentence Assembly*. Standardized receptive and expressive language index scores were then calculated for each participant by summing the three subtests in each domain, as prescribed in the protocols for the language assessment measure.

The Multidimensional Social Competence Scale (MSCS; Yager & Iarocci, 2013) is a seventy-seven-item measure in which participants indicated on a five-point Likert scale (not true/almost never true; rarely true; sometimes true; often true; very true/almost often true) a response to statements on social motivation, inferencing, knowledge, empathy, verbal and non-verbal skills and emotion regulation. In addition to receiving a total social competency score, participants received a score on seven subscales assessing social motivation, social inferencing, empathy, social knowledge, verbal conversational skills, nonverbal sending skills, and emotion regulation. Example items on this scale include, *"I prefer to spend time alone (e.g., I am most content when left on my own)", "I recognize when people are trying to take advantage of me", "I change my behaviour to suit the situation. For example, I might be more polite/formal around authority figures like teachers or supervisors but be more casual around peers"*.

Several well-established questionnaires used as screening protocols for ASD symptoms were administered. Questionnaires were completed, and responses were recorded using the Qualtrics Survey Software. The Autism Quotient (AQ; Baron-Cohen et al., 2001) is a fifty-item measure using a four-point Likert scale (definitely disagree; slightly disagree; slightly agree; definitely agree) to assess the degree to which an individual has traits associated with autism. For this measure, participants received a total score as well as a score on five subscales that assessed social skills, attention switching, attention to detail, communication, and imagination. Items assessing social and attentional domains include *"I find social situations easy"* and *"I often notice small sounds when others do not".* The Broad Autism Phenotype Questionnaire (BAPQ; R. S. Hurley et al., 2007) is a thirty six-item questionnaire that was completed to measure autistic traits. Participants indicated a response on a six-point Likert scale (very rarely; rarely; occasionally; somewhat often; often, very often) on a variety of personality statements. In addition to a total score, participants received a score on aloofness, pragmatic language ability, and rigidity. Items assessing withdrawn behaviours and pragmatic language ability include *"I like being around other people"* and *"I find it hard to get my words out smoothly".*

2.1.3 Analysis

Items on the auditory and visual statistical learning tasks were analyzed for accuracy and above-chance performance. As a 2AFC, the chance rate of the test-phase of the auditory statistical learning task was 50%, whereas the visual statistical learning test phase included 2AFC, 3AFC, and 4AFC components, thus having chance levels of 50%, 33%, and 25%, respectively. Overall accuracy scores from the auditory statistical learning task were calculated by averaging participants correct responses on all items. Visual statistical learning accuracy included averaging the items on each separate component followed by averaging correct responses on all 42 test items to create an overall mean accuracy score. Overall mean accuracy scores from both tasks as well as mean accuracy scores from the separate components on the visual statistical learning task were then used to examine possible relationships between statistical learning, receptive and expressive language, social competency, and autistic traits.

The CELF-5 language assessment is intended to assess receptive and expressive language abilities from individuals aged 5.0 to 21.11. Therefore, participants above this age were excluded from the analyses (*N* = 5). Those identified as outliers (± 2SD from the mean values; *N* = 3) on total questionnaire measures including the MSCS, AQ, and BAPQ, rather than questionnaire subscale measures were also excluded. One additional participant was excluded for not completing the visual statistical learning task.

The MSCS was used to explore the relationships between social competency, language, and statistical learning. Participants total scores assessing social competency as well as subscale scores measuring social motivation, social inferencing, empathy, social knowledge, verbal conversational skills, nonverbal sending skills, and emotion regulation were analyzed.

Lastly, total and subscale scores on the AQ and BAPQ were used to explore the relationship between autistic traits and statistical learning. For the AQ, this included total scores, assessing autistic traits as well as scores measuring social skills, attention switching, attention to detail, communication, and imagination. For the BAPQ, total scores that assessed autistic traits were included in the analysis in addition to scores measuring aloofness, pragmatic language, and rigidity. Total AQ and BAPQ scores were analyzed to determine the range of scores observed.

All data were normally distributed and therefore, Pearson bivariate correlations were used to explore the possible relationship between statistical leaning and language, statistical learning and social competency, and statistical learning and autistic traits. The Benjamini-Hochberg false discovery rate procedure was used to adjust for multiple comparisons with a false discovery rate of 25%. Finally, mediation analyses were conducted on all social competency scales that were significantly correlated with both receptive language and a measure of statistical learning.

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2.2 Results

2.2.1 Above Chance Performance on Statistical Learning Tasks

Performance was found to be reliably above chance for overall auditory (64%, $t_{(94)}$ = 57.08, $p < .001$, *Cohen's d* = 5.82) and visual (58%, $t_{(94)}$ = 42.68, $p < .001$, *Cohen's d* = 4.46) statistical learning tasks. In addition, performance was reliably above chance for visual pair completion (59%, $t_{(94)}$ = 23.52, $p < .001$, *Cohen's d* = 2.36), triplet completion (55%, $t_{(94)}$ = 20.55, $p < .001$, *Cohen's d* = 2.12), 2AFC recognition (68%, $t_{(94)}$ = 43.61, $p < .001$, *Cohen's d* = 4.53), 4AFC recognition (41%, $t_{(94)}$ = 18.38, $p < .001$, *Cohen's d* = 1.86), 2AFC pair recognition (64%, $t_{(94)}$ = 28.61, $p <. 001$, *Cohen's d* = 2.91), and 4AFC pair recognition (44%, $t_{(94)}$ = 21.18, $p < .001$, *Cohen's d* = 2.20).

2.2.2 Relating Statistical Learning and Language

Visual statistical learning accuracy was found to be significantly correlated with receptive language ability ($r_{(94)} = .31$, $p = .002$) indicating that decreased visual statistical learning abilities are related to decreased receptive language abilities however, contrary to our predictions, auditory statistical learning was not found to be significantly related to receptive language ability ($r_{(94)} = .08$, $p = .45$).

2.2.3 Relating Statistical Learning and Social Competency

Visual statistical learning was not significantly related to total social competency scores ($r_{(94)} = .18$, $p = .09$), nor the MSCS subscales social motivation ($r_{(94)} = -.08$, $p = .45$), social inferencing (r (94) = .12, $p = .26$), verbal conversation skills, ($r_{(94)} = .09$, $p = .41$), or emotional regulation ($r_{(94)} = .09$, $p = .41$). However, it was found to be significantly related to social competency skills including empathy ($r_{(94)} = .26$, $p = .01$), social knowledge ($r_{(94)} = .24$, $p = .02$), and nonverbal sending skills ($r_{(94)} = .20$, $p = .05$) in that increased visual statistical learning

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abilities were related to increased social competency skills. However, auditory statistical learning was not found to be significantly related to social competency. Please see Table 1 for correlation values, as well as means and standard deviations for all variables.

Table 1: Bivariate correlations between Statistical Learning, Language, Social Competency, and Autistic Traits (N = 95).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Auditory Accuracy	--	.267	.447	.334	.217	.246	.258	.149	.861	.462	.284	.485	.004**	.001**
2. Visual Accuracy	.12	--	.002**	.181	.088	.012*	.018*	.047*	.452	.264	.405	.414	.627	.775
3. Receptive	.08	.31**	--	.000**	.014*	.392	.001**	.013*	.431	.018*	.013*	.044*	.863	.192
4. Expressive	.10	.14	.55**	--	.054	.025*	.001**	.038*	.357	.664	.047*	.394	.070	.769
5. MSCS Total	.13	.18	.25*	.20	--	.000**	.000**	.000**	.000**	.000**	.000**	.000**	.003**	.001**
6. *Empathy*	.12	.26*	.09	.23*	.65**	--	.000**	.000**	.000**	.000**	.011*	.439	.795	.185
7. *Social Knowledge*	.12	.24*	.33**	.34**	.71**	.51**	--	.000**	.311	.000**	.000**	.000**	.370	.297
8. *Nonverbal Sending Skills*	.15	.20*	.26*	.21*	.66**	.56**	.46**	--	.000**	.001**	.036*	.230	.081	.086
9. *Social Motivation*	-.02	-.08	-.08	-.10	.59**	.42**	.11	.49**	--	.000**	.446	.125	.002*	.000**
10. *Social Inferencing*	.08	.12	.18	.05	.77**	.41**	.49**	.34*	.40**	--	.000**	.000**	.007*	.002*
11. *Verbal Skills*	.11	.09	.25*	.21*	.68**	.26*	.56**	.22*	.08	.46**	--	.000**	.092	.048
12. *Emotion Regulation*	.07	.09	.21*	.09	.65**	.08	.40**	.12	.16	.54**	.59**	--	.007*	.043
13. AQ	-.29**	.05	.02	-.19	-.30**	-.03	-.09	-.18	-.31**	-.27**	-.17	-.28**	--	.000**
14. BAPQ	-.32**	-.03	.14	-.03	-.34**	-.14	-.11	-.18	-.37**	-.32**	-.20*	-.21*	.67**	--
Mean	.64	.58	98.75	101.59	294.43	43.99	47.62	43.64	40.47	41.57	39.10	38.04	18.01	106.31
S.D.	.11	.13	10.36	8.35	27.64	5.18	4.39	5.87	6.83	5.54	6.31	7.21	5.40	24.28

Note. *$p < .05$; **$p < .01$. Correlation values are presented on the bottom left and corresponding p values are presented on the upper right. P-values listed as .000 represent p-values < 0.001

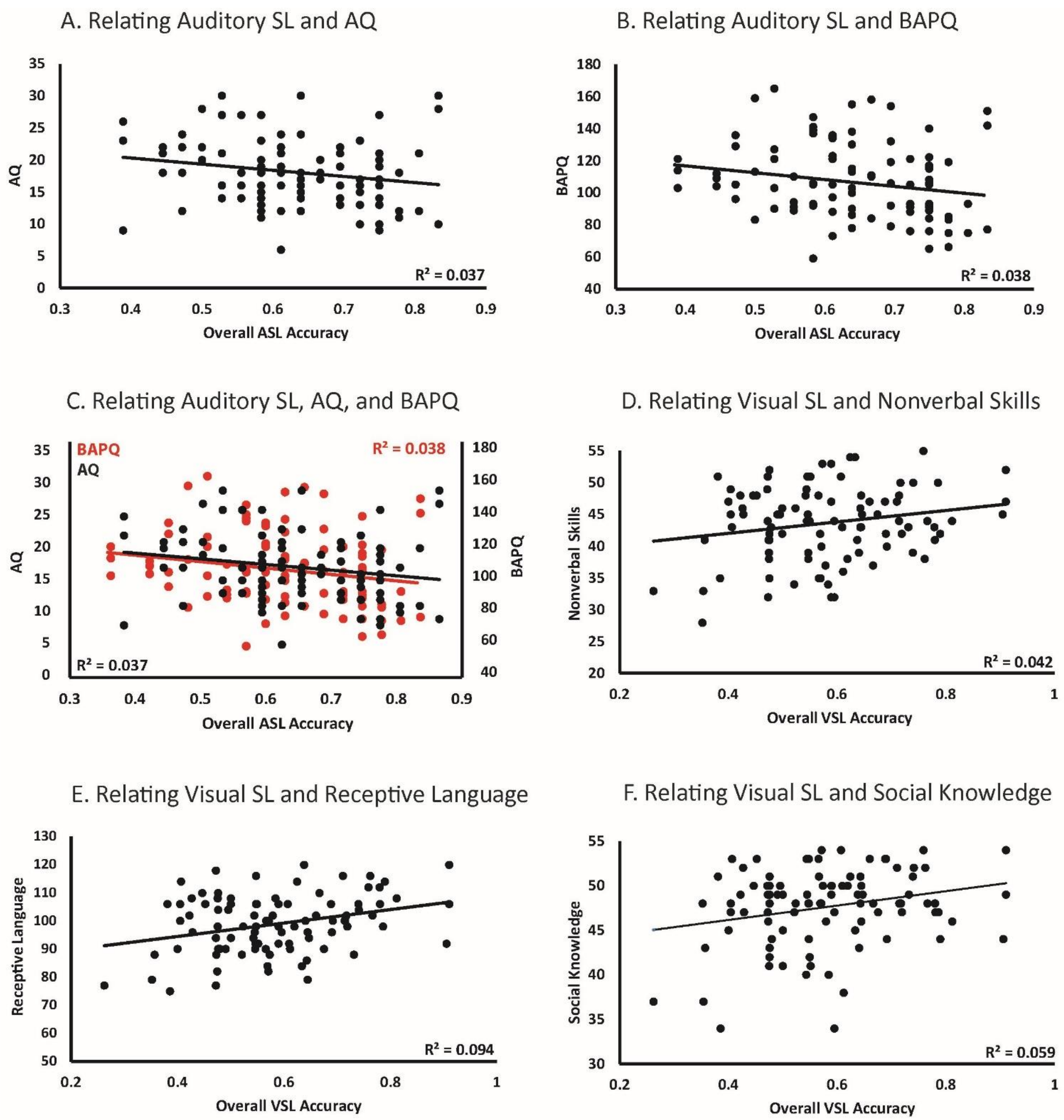

Figure 3: Relating (A) auditory statistical learning and total AQ scores (B) auditory statistical learning and total BAPQ scores (C) auditory statistical learning, total AQ (black), and total BAPQ scores (red) (D) visual statistical learning and MSCS nonverbal sending skills (E) visual statistical learning and receptive language (F) visual statistical learning and social knowledge.

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2.2.4 Receptive Language as a Mediating Variable

Both visual statistical learning and receptive language were significantly correlated with the social competency subscale of *Social Knowledge.* As such, a series of multiple linear regression analyses were used to determine if receptive language ability significantly mediated the relationship between visual statistical learning abilities and social knowledge **(Figure 4).** Prior to completing these analyses, the following conditions were shown to be true: (1) statistical learning was significantly related to social knowledge, (2) statistical learning was significantly related to receptive language, (3) receptive language was significantly related to social knowledge after controlling for statistical learning, and (4) the impact of statistical learning on social knowledge was significantly less after controlling for receptive language abilities. Our regression analyses showed that receptive language had full mediating effects on social knowledge. The relationship between visual statistical learning and social knowledge not only became statistically non-significant, but also exhibited a significant drop in predictive nature when receptive language ability was added into the model. The indirect effect (ab = .085, *SE* = 1.37, 95% [0.945, 6.143]) was judged to be statistically significant using the Sobel (1983) test ($z = 2.05$, $p = .040$). Thus, once the contribution of receptive language ability was accounted for, visual statistical learning only significantly contributed to social knowledge indirectly, through receptive language. Additionally, receptive language ability accounted for 7% ($R^2 = .069$) of participants social knowledge scores and visual statistical learning abilities accounted for 2% ($R^2 = .023$) of participants social knowledge scores. Combined, receptive language and visual statistical learning account for 13% ($R^2 = .128$) of the variance in our samples social knowledge scores ($F_{(2, 92)} = 6.77$, $p = .002$).

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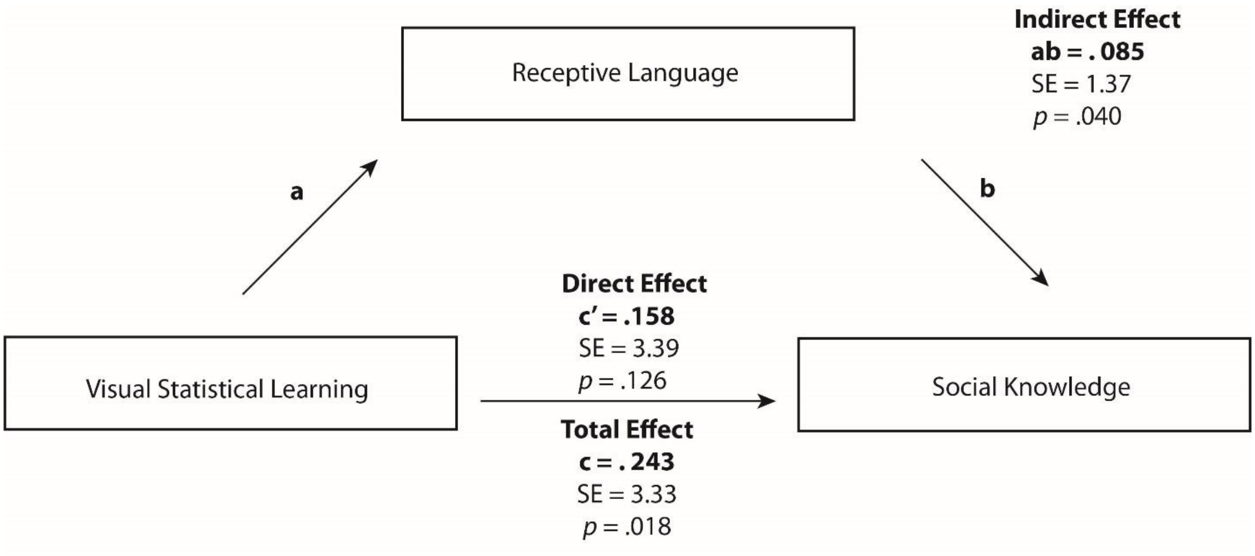

Figure 4: Mediation model testing the effect of receptive language ability on visual statistical learning and social knowledge.

To test the directionality of this relationship, an additional mediation analysis was performed to determine whether receptive language specifically mediated the relationship between visual statistical learning and social knowledge, or if social knowledge could also have acted as a mediator between the two variables. The mediation analysis revealed that when social knowledge was included as a mediator between visual statistical learning and receptive language, the indirect pathway (ab = .065, *S*E = 2.80, 95% [1.181, 12.029]) was only marginally significant ($z = 1.80$, $p = .072$), therefore providing strong evidence of directionality as proposed in the original model. It should be noted, however, that the total effect predicting receptive language abilities from visual statistical learning was statistically significant, further confirming that the overall effect of visual statistical learning on receptive language was statistically significant. Our data therefore suggest that there is a directional relationship between visual statistical learning abilities, receptive language, and social knowledge where receptive language specifically mediates this relationship.

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Additionally, the social competency subscale of *Nonverbal Sending Skills* was significantly related to both receptive language and visual statistical learning. As such, we conducted a regression to test whether receptive language mediated the relationship between visual statistical learning and nonverbal sending skills **(Figure 5)**, which revealed a partially mediated pathway (ab = .066, *SE* = 1.70, 95% [0.470, 6.692], $z = 1.73$, $p = .083$) where the direct effect (the remaining effect of visual statistical learning on nonverbal sending skills when receptive language has been included in the analysis) was not significant once receptive language was included. Thus, when the contribution of receptive language was accounted for, visual statistical learning only contributed significantly to nonverbal sending skills indirectly, through receptive language. Similar to the above mediation model, the total effect predicting nonverbal sending skills from visual statistical learning was statistically significant, indicating that visual statistical learning abilities do significantly predict receptive language abilities.

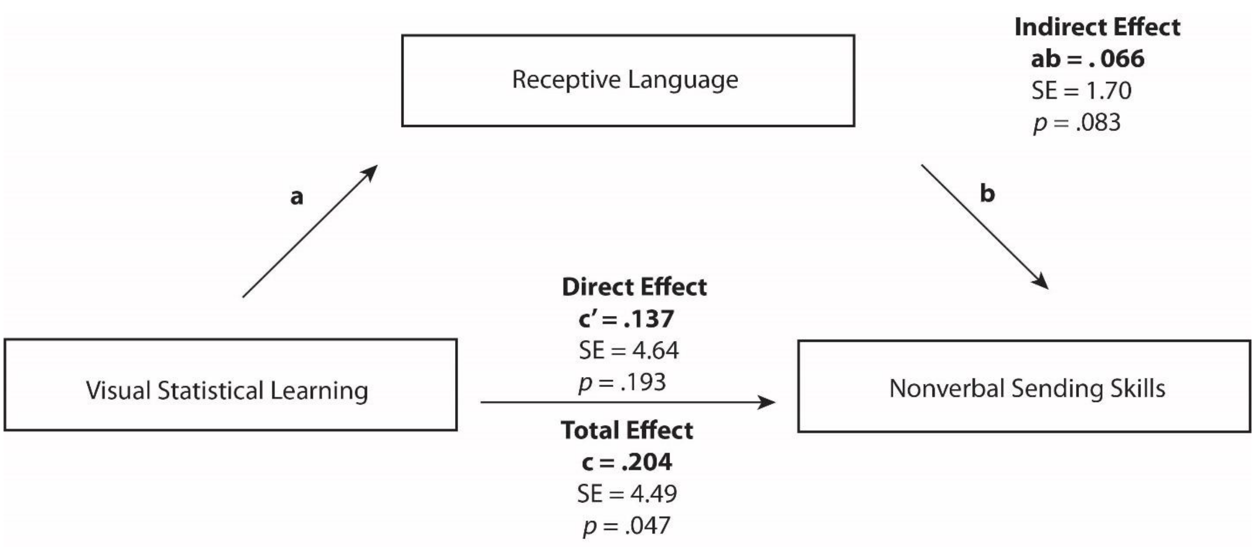

Figure 5: Mediation model testing the effect of receptive language ability on visual statistical learning and nonverbal sending skills.

2.2.5 Range of Autistic Traits

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Our results showed that total sores on the AQ ranged 6 to 30 and average responses on the individual items on the BAPQ ranged from 1.64 to 5.33 where a cut-off value of 32+ on the AQ and an average of 3.14 across all 36 individual items on the BAPQ is useful in distinguishing individuals with clinical levels of autistic traits (Baron-Cohen et al., 2001;Hurley, Losh, Parlier, Reznick, & Piven, 2007).

2.2.6 Relating Statistical Learning and Autistic Traits

Auditory statistical learning was found to be significantly related to total scores on the AQ ($r_{(94)}$ -.29, p = .004) and BAPQ ($r_{(94)}$ = -.32, p = .001) suggesting that, as predicted, decreased statistical learning abilities in the auditory domain are related to increased autism symptom severity. However, this same relationship was not observed for overall visual statistical learning (AQ: $r_{(94)}$ = .05, p = .63, BAPQ; $r_{(94)}$ = -.03, p = .78), or any of the additional visual statistical learning scores examining pattern recognition and completion.

2.2.7 Sensory Profile Measure Post Hoc Analysis

A post-hoc analysis was performed to explore potential relationships between basic sensory processing and auditory and visual statistical learning abilities using the sensory profile-2 (SP-2; Dunn, 1999). Participants completed an additional study in lab investigating sensory sensitivities and autistic traits (Schulz & Stevenson, 2018) where they completed the 60-item scale that assessed sensory function. This post-hoc analysis allowed us to explore whether statistical learning performance was a result of learning or a result of differences in sensory representations of the auditory and visual stimuli. Auditory and visual statistical learning was not found to be related to overall sensory processing ($r_{(94)}$ = .002, p = .987, $r_{(94)}$ = .053, p = .612), respectively . Therefore, our results suggest that performance on the auditory and visual tasks are

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a result of learning the transitional probabilities within the syllable and shape presentations rather than differential sensory representations of the stimuli.

2.3 Discussion

The purpose of this study was to examine the relationship between statistical learning, language, and social competency, and a number of novel relationships were observed. First, our results partially confirmed our *a priori* hypothesis that statistical learning abilities, particularly visual statistical learning abilities, are directly related to both increased language comprehension and social competency abilities. Second, our mediation results provide support for a specific directional relationship between visual statistical learning abilities, receptive language, and social competency such that the relationship between visual statistical learning and social competency is mediated by receptive language abilities. Third, while auditory and visual statistical learning were both significantly above chance levels, these two measures of statistical learning were independent of each other, suggesting that separate processes underlie each. Finally, our data support the hypothesis that statistical learning in the auditory domain, but not the visual, is anticorrelated with autistic traits such that individuals with higher levels of autistic traits exhibited weaker auditory statistical learning.

Consistent with previous research, our results show that visual statistical learning abilities are related to receptive language (Daltrozzo et al., 2017) in that an increased ability to learn patterns in the visual domain is related to increased language comprehension. It was also found that increased visual statistical learning abilities were related to increased social competency skills, suggesting that visual statistical learning is important for understanding the emotions of oneself and others, how to act appropriately in social situations, as well as using appropriate nonverbal communication. Indeed, it has been suggested that successful social interactions

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depend on a strong ability to pick up on temporal patterns that occur in facial expressions, gestures, and other non-verbal cues (Lieberman, 2000). This ability to pick up on subtle sequences of non-verbal information allow us to draw inferences about others emotional states and intentions during social interactions. Previous research has linked visual statistical learning and social abilities including adaptive social functioning (Jeste et al., 2015). However, this relationship, to our knowledge, has only been reported in ASD populations. This is therefore the first study to identify a relationship between visual statistical learning, language, and social abilities in TD individuals.

One novel finding that has not yet been reported in the literature was that the relation between visual statistical learning and social knowledge was significantly mediated by receptive language ability. Rather than a direct relationship between visual statistical learning abilities and social knowledge, language comprehension therefore helps to clarify the observed relationship between these two variables. Our mediation results therefore show that visual statistical learning abilities impact receptive language abilities which in turn, impact social knowledge. This same directional relationship was not observed when social knowledge was included as the mediator rather than the dependent variable, supporting the directional relationship between visual statistical learning, receptive language, and social knowledge. Further, when examining whether receptive language significantly mediates the relationship between visual statistical learning and nonverbal sending skills, the mediated effect was found to be marginally significant, indicating that some of the variability in our model is explained by this indirect pathway and further investigation into the nature of this mediated relationship is warranted. Although prior research has linked statistical learning and language in TD individuals, only those using ASD populations have previously found correlational links between auditory (Scott-Van Zeeland et al., 2010) and visual (Jeste et al., 2015) statistical learning and social competency skills. Our results therefore provide novel evidence, showing that this same relationship between statistical learning and social competency is apparent in non-ASD populations. Taken together, these findings highlight the important role that language plays in understanding the relationship between statistical learning and social competency in the general population. Also, our findings highlight the importance of examining both total and subscale scores of social competencies to understand the distinct relationships they can have with statistical learning and language comprehension.

It is surprising that we did not find a relationship between auditory statistical learning and language abilities, as auditory statistical learning has been shown to be associated with vocabulary (Evans et al., 2009) and other broader language skills (Misyak & Christiansen, 2012). There are a number of possible reasons for this discrepant result. Perhaps the clearest distinction between this work and previous research is that most research that has linked auditory statistical learning and language abilities has focused on infants or young children (Estes et al., 2016; Evans et al., 2009; Gomez & Gerken, 1999; Lany, 2014; Lany et al., 2018; Newman et al., 2006), while in the current study, data was from adult participants with fully-developed language abilities. It may be that statistical learning is an important predictor of early language development or in the rate of language development, but that this relationship diminishes as language development plateaus. Likewise, infant studies use differing metrics of statistical learning, such as looking time measurements, while in the current study, learning was measured by recording explicit responses from adult participants. The discrepancy between our findings and those of previous studies relating auditory statistical learning and language could therefore be attributed to subtle task differences in addition to using different measures of learning.

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It could also be that attention is driving the relationship between visual statistical learning and receptive language abilities. It has been found that attention influences the relationship between visual statistical learning abilities and receptive language at both the behavioural and neurophysiological level (Daltrozzo et al., 2017). Moreover, auditory statistical learning may depend, at least in part, on attention (Toro, Sinnett, & Soto-Faraco, 2005), and is similarly involved in visual statistical learning (Baker, Olson, & Behrmann, 2004). Attention helps language users map words, sentences, and images onto their appropriate referents and before they can accomplish this, they must first attend to the patterns that are occurring in their environment (Saffran, Senghas, & Trueswell, 2001). Here, our methodology mirrored previous paradigms in both the auditory and visual domains. The previously established visual paradigm includes instructing participants to *"try their best to remember the shapes that were presented"* (Siegelman et al., 2016) while participants actively attended the presentations, whereas in the auditory paradigm, participants were simply instructed to *"colour until the sounds stopped playing"* and were thus actively attending to a secondary task as opposed to the auditory stimuli (Saffran, Newport, Aslin, Tunick, & Barrueco, 1997). Thus, attention may have impacted subsequent learning from our visual statistical learning task, as well as the relationship between our visual statistical learning measure and receptive language abilities.

Likewise, we found that only visual statistical learning was significantly related to social competency, in contrast to our hypothesis that learning patterns in general should be important for predicting the actions of others and relying on previous patterns and relationships during social interactions to help guide current ones. While the aforementioned impact of attention is a possible explanation here, it could also be that given that the visual and auditory statistical learning tasks differed in their probabilities, and the way learning was measured, the visual statistical learning task used here may be more closely related to the complexities of real social interactions where sequences can be less predictable than those presented in the auditory statistical learning task.

Auditory and visual statistical learning were also shown to be independent of one another. This finding aligns with previous research (Siegelman & Frost, 2015). Individual sensitivities to the probabilities that occur in auditory and visual tasks do exist and are not uniform across auditory and visual modalities or across stimuli. Therefore, it could be that statistical learning is dependent on the sensory modality of the input such that auditory statistical learning abilities are important for aspects of language outside of those measured here, where visual abilities are important for non-verbal abilities, such as learning the unspoken rules of social language. The results from our study provide support for this difference and suggest that distinct processes may underlie how auditory and visual patterns are processed. It is however, important to note again that our statistical learning tasks differed from one another, making it difficult to determine whether the lack of relationship between the two tasks is a result of methodological differences or the modality in which learning occurred.

In addition to auditory and visual statistical learning differing in their relationship with receptive language and social competencies, and not relating to one another, they were also differently related to ASD traits. Those with higher autistic traits tended to perform worse on the auditory statistical learning task, which is consistent with other studies investigating statistical learning in ASD using similar auditory statistical learning tasks that require implicit, sequence learning (Jeste et al., 2015; Scott-Van Zeeland et al., 2010). Visual statistical learning, however, was not shown to be related to autistic traits despite being related to autism related social competency. Given the apparent social competency difficulties in autism, it is surprising that we found a relation between visual statistical learning, language, and social competency but not visual statistical learning and autistic traits. Research examining visual processing in autism has reported enhanced performance on visual tasks that require both detection and discrimination however, this enhanced performance is limited to simple over complex visual stimuli (Bertone, Mottron, Jelenic, & Faubert, 2005; Caron, Mottron, Berthiaume, & Dawson, 2006). Comparable visual processing abilities in TD and ASD individuals could therefore explain why auditory statistical learning was more strongly related to autistic traits than visual statistical learning abilities.

Further, the idea of weak central coherence as a default cognitive style in autism (Frith, 1989) could also explain why we saw different relationships between autistic traits and our auditory and visual statistical learning tasks. As mentioned above, the weak central coherence hypothesis posits that when individuals with autism are not instructed, they tend to focus on finer details of an object or situation however, when instructed, these same individuals are able to draw together smaller pieces of information into larger, more meaningful patterns. In our auditory statistical learning task, we did not instruct our participants to pay attention to the patterns. Instead, we had them passively listen to the sounds while engaged in a colouring task. As a result, participants may have focused more on the finer details during this task instead of processing the patterns which could explain our finding that autistic traits were related to auditory statistical learning abilities. However, the idea of weak central coherence as a cognitive style also suggests that individuals with autism can in fact process at the global level when instructed to do so. Thus, in our visual statistical learning task, where participants were instructed to watch the shapes, they were more likely to focus on the patterns that were presented rather than the individual shapes. Likewise, these instructions could explain why we did not find a relationship between autistic traits and visual statistical learning abilities.

Despite this, during statistical learning, individuals are learning how things are grouped in the environment and there are a number of neurobiological accounts of autism that, in their own different ways, predict an issue with statistical learning. The predictive coding framework suggests that our experiences are influenced by incoming sensory information as well as prior perceptual experiences (Pellicano & Burr, 2012; Stevenson, Toulmin, et al., 2017). Atypical sensory perception in autism can be explained through this framework, suggesting that these individuals do not integrate incoming sensory information and prior knowledge in a typical manner, either due to a decreased ability to form reliable probability maps or an overweighting of incoming sensory information. In either case, this framework predicts a decreased ability to utilize patterns and temporal statistics within in the environment. The above-mentioned neurobiological abnormalities that impact cognitive functioning in ASD therefore suggest that autistic individuals are processing and responding to statistical probabilities in the environment differently than their TD peers however, additional research is needed in order to determine how these individuals are processing these patterns and whether this differential processing could explain the language and social competency difficulties observed in ASD.

Our results therefore provide novel evidence suggesting the relationship between statistical learning, language, and social competency is not restricted to autism, but can also be observed in non-ASD adult populations. Further, our mediation results provide evidence for a directional relationship between statistical learning, language comprehension, and social competency that, to our knowledge, has not yet been reported in the literature. Taken together, our findings suggest that reduced statistical learning abilities may cascade into language and

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socio-communicative impairments, preventing individuals from engaging in opportunities or picking up on cues that would improved language learning.

2.3.1. Future Directions

Although both auditory and visual statistical learning tasks used in the current study have been well established, there are several areas for improvements that should be considered in future research. First, both statistical learning tasks assess recognition after familiarization, which may reflect more explicit types of learning rather than implicit. Second, the test items in the auditory task are all identical in levels of difficulty and share similar properties, where participants are required to compare two words and pick the one that is most familiar.

Recent work in statistical learning has attempted to improve some of these shortcomings by measuring learning more implicitly, while participants are exposed to the familiarization phase (Batterink & Paller, 2017;Batterink & Reber, 2015;Batterink et al., 2015). In this task, participants are required to respond to a selected target occurring in a continuous stream of syllables, with faster reaction times indexing better processing of predictable targets. In turn, attention can be monitored by examining accuracy scores (i.e. percentage of correct/incorrect responses can determine guessing). New methodologies such as using ‘temporal community structures’ (Schapiro, Rogers, Cordova, Turk-Browne, & Botvinick, 2013; Schapiro, Turk-Browne, Norman, & Botvinick, 2016) are another potential avenue for future statistical learning tasks, allowing researchers to control transitional probabilities in a more consistent manner. These techniques may (1) allow for more direct comparison across sensory modalities, (2) measure statistical learning not only after familiarization, but also the rate of statistical learning during familiarization, and (3) improve the ecological validity of statistical learning tasks by mimicking real world learning conditions that involve more complex temporal relationships than those presented by transitional probabilities used in previous statistical learning tasks.

Given that past research has found evidence for reduced statistical learning abilities in ASD at both the behavioral and neural level, it might also be beneficial to combine these methods to better understand how auditory and visual statistical learning is processed in autism and other developmental disabilities. Further, using EEG and fMRI methods to examine statistical learning will enable researchers to understand these processes in minimally verbal, low-functioning children and adults, revealing valuable information about pattern learning beyond those provided by behavioral measures alone.

2.3.2 Conclusions

Here, we have highlighted the important role that statistical learning plays in language ability and social competency. Our results demonstrate a clear relationship between statistical learning, language, and social competency abilities as well as statistical learning and autistic traits. Furthermore, that the relationship between statistical learning and social competency, specifically social knowledge, is mediated by receptive language ability suggesting that impaired statistical learning abilities cascade into language and social competency abilities. Interestingly, this same directional effect was not observed when social knowledge was included as the mediator between visual statistical learning and receptive language. It is important to note that the methodological differences between the auditory and visual statistical learning tasks may have accounted for the differential relationships that emerged between auditory and visual statistical learning and language, social communication, and autistic traits. If the ability to learn patterns in general is in fact important for language and social competency abilities, it could be argued that both tasks, having tapped into this ability, should have related to language and social

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skills. Future work should therefore match statistical learning tasks in order to make conclusions about whether one type of statistical learning is more important for language and social communication and another is more related to autism symptom severity. Despite this, the results from the current study provide valuable insight into the role that statistical learning plays in both language and social abilities. Language and social difficulties that are a result of impaired statistical learning can have a negative impact on many aspects of an individual's life. For instance, an inability to understand instructions could result in poor academic achievement and difficulties understanding others could result in negative interpersonal relationships. If untreated, issues related to poor language comprehension and social competency can extend beyond adolescence and into adulthood, causing further problems related to employment and education. With that in mind, research has shown that training programs aimed at improving temporal and sequential processing capacities can bolster the recognition of speech and non-speech temporal sequences in children with language impairments (Merzenich et al., 1996) as well as language processing in TD adults (Smith, Conway, Bauernschmidt, & Pisoni, 2015). Therefore, incorporating activities into therapies and interventions that encourage pattern and sequence learning may help TD and autistic individuals learn these patterns and probabilities more readily. In turn, setbacks that result from poor language and social competency can be mitigated.

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2.4 References

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

Arciuli, J. (2017). The multi-component nature of statistical learning. *Phil. Trans. R. Soc. B, 372*(1711), 20160058. doi: 10.1098/rstb.2016.0058

Arciuli, J., & Simpson, I. C. (2012). Statistical learning is related to reading ability in children and adults. *Cognitive science, 36*(2), 286-304. doi: http://dx.doi.org/10.1111/j.1551-6709.2011.01200.x

Aslin, R. N., Saffran, J. R., & Newport, E. L. (1998). Computation of conditional probability statistics by 8-month-old infants. *Psychological Science, 9*(4), 321-324.

Baker, C. I., Olson, C. R., & Behrmann, M. (2004). Role of attention and perceptual grouping in visual statistical learning. *Psychological Science, 15*(7), 460-466.

Baldwin, D., Andersson, A., Saffran, J., & Meyer, M. (2008). Segmenting dynamic human action via statistical structure. *Cognition, 106*(3), 1382-1407. doi: http://dx.doi.org/10.1016/j.cognition.2007.07.005

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

Batterink, L. J., & Paller, K. A. (2017). Online neural monitoring of statistical learning. *cortex, 90*, 31-45.

A version of this paper is under review in *Scientific Reports* (Parks & Stevenson, *under review*).

Batterink, L. J., & Reber. (2015). Functional differences between statistical learning with and without explicit training. *Learning & memory (Cold Spring Harbor, N.Y.), 22*(11), 544-556. doi: 10.1101/lm.037986.114

Batterink, L. J., Reber, P. J., Neville, H. J., & Paller, K. A. (2015). Implicit and explicit contributions to statistical learning. *Journal of Memory and Language, 83*, 62-78. doi: http://dx.doi.org/10.1016/j.jml.2015.04.004

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.

Bogaerts, L., Siegelman, N., & Frost, R. (2016). Splitting the variance of statistical learning performance: A parametric investigation of exposure duration and transitional probabilities. *Psychonomic bulletin & review*, *23*(4), 1250-1256. doi: http://dx.doi.org/10.3758/s13423-015-0996-z

Bölte, S., Westerwald, E., Holtmann, M., Freitag, C., & Poustka, F. (2011). Autistic traits and autism spectrum disorders: The clinical validity of two measures presuming a continuum of social communication skills. *Journal of Autism and Developmental Disorders, 41*(1), 66-72.

Boucher, J. (2012). Research review: structural language in autistic spectrum disorder - characteristics and causes. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *53*(3), 219-233. doi: 10.1111/j.1469-7610.2011.02508.x

Brown, J., Aczel, B., Jiménez, L., Kaufman, S. B., & Grant, K. P. (2010). Intact implicit learning in autism spectrum conditions. *The quarterly journal of experimental psychology*, *63*(9), 1789-1812.

A version of this paper is under review in *Scientific Reports* (Parks & Stevenson, *under review*).

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

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

Cleeremans, A., & McClelland, J. L. (1991). Learning the structure of event sequences. *Journal of Experimental Psychology: General, 120*(3), 235.

Constantino, J. N., Davis, S. A., Todd, R. D., Schindler, M. K., Gross, M. M., Brophy, S. L., . . . Reich, W. (2003). Validation of a brief quantitative measure of autistic traits: comparison of the social responsiveness scale with the autism diagnostic interview-revised. *Journal of Autism and Developmental Disorders, 33*(4), 427-433.

Conti-Ramsden, G. (2003). Processing and linguistic markers in young children with specific language impairment (SLI). *Journal of Speech, Language, and Hearing Research, 46*(5), 1029-1037.

Conway, C. M., Bauernschmidt, A., Huang, S. S., & Pisoni, D. B. (2010). Implicit statistical learning in language processing: Word predictability is the key. *Cognition, 114*(3), 356-371.

Creel, S. C., Newport, E. L., & Aslin, R. N. (2004). Distant Melodies: Statistical Learning of Nonadjacent Dependencies in Tone Sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*(5), 1119-1130. doi: http://dx.doi.org/10.1037/0278-7393.30.5.1119

A version of this paper is under review in *Scientific Reports* (Parks & Stevenson, *under review*).

Cuthbert, B. N. (2014). The RDoC framework: facilitating transition from ICD/DSM to dimensional approaches that integrate neuroscience and psychopathology. *World Psychiatry, 13*(1), 28-35.

Daltrozzo, J., Emerson, S. N., Deocampo, J., Singh, S., Freggens, M., Branum-Martin, L., & Conway, C. M. (2017). Visual statistical learning is related to natural language ability in adults: An ERP study. *Brain and Language, 166*, 40-51. doi: http://dx.doi.org/10.1016/j.bandl.2016.12.005

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

Ellis, E. M., Gonzalez, M. R., & Deák, G. O. (2014). Visual prediction in infancy: What is the association with later vocabulary? *Language Learning and Development*, *10*(1), 36-50. doi: http://dx.doi.org/10.1080/15475441.2013.799988

Elman, J. L. (1990). Finding structure in time. *Cognitive science*, *14*(2), 179-211.

Elman, J. L. (1991). Distributed representations, simple recurrent networks, and grammatical structure. *Machine learning, 7*(2-3), 195-225.

Estes, K. G., Gluck, S. C.-W., & Grimm, K. J. (2016). Finding patterns and learning words: Infant phonotactic knowledge is associated with vocabulary size. *Journal of experimental child psychology, 146*, 34-49.

Evans, J. L., Saffran, J. R., & Robe-Torres, K. (2009). Statistical learning in children with specific language impairment. *Journal of Speech, Language, and Hearing Research, 52*(2), 321-335.

Frith, U. (1989). *Autism: Explaining the enigma* (Vol. 1989): Wiley Online Library.

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

Gómez, R. L. (2002). Variability and detection of invariant structure. *Psychological Science, 13*(5), 431-436.

Gomez, R. L., & Gerken, L. (1999). Artificial grammar learning by 1-year-olds leads to specific and abstract knowledge. *Cognition, 70*(2), 109-135.

Graf Estes, K., Evans, J. L., Alibali, M. W., & Saffran, J. R. (2007). Can infants map meaning to newly segmented words?: Statistical segmentation and word learning. *Psychological Science, 18*(3), 254-260. doi: http://dx.doi.org/10.1111/j.1467-9280.2007.01885.x

Haebig, E., Saffran, J. R., & Ellis Weismer, S. (2017). Statistical word learning in children with autism spectrum disorder and specific language impairment. *Journal of Child Psychology and Psychiatry*. doi: http://dx.doi.org/10.1111/jcpp.12734

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

Hay, J. F., Pelucchi, B., Estes, K. G., & Saffran, J. R. (2011). Linking sounds to meanings: Infant statistical learning in a natural language. *Cognitive psychology, 63*(2), 93-106.

Hayes, J. R., & Clark, H. H. (1970). Experiments in the segmentation of an artificial speech analog. *Cognition and the development of language*, 221-234.

Hill, K. R., Hayes, M. A., & Harrison, P. (2008). Method of administering licensing of use of copyright works: Google Patents.

Hudry, K., Chandler, S., Bedford, R., Pasco, G., Gliga, T., Elsabbagh, M., . . . Charman, T. (2014). Early language profiles in infants at high-risk for autism spectrum disorders. *Journal of Autism and Developmental Disorders, 44*(1), 154-167. doi: http://dx.doi.org.proxy1.lib.uwo.ca/10.1007/s10803-013-1861-4

Hudry, K., Leadbitter, K., Temple, K., Slonims, V., McConachie, H., Aldred, C., . . . Consortium, P. (2010). Preschoolers with autism show greater impairment in receptive compared with expressive language abilities. *International Journal of Language & Communication Disorders, 45*(6), 681-690. doi: 10.3109/13682820903461493

Hurley, R., Losh, M., Parlier, M.,Reznick, J., & Piven, J. (2007). The Broad Autism Phenotype Questionnaire. *Journal of Autism and Developmental Disorders, 37*, 1679-1690. doi: 10.1007/s10803-006-0299-3

Hurley, R. S., Losh, M., Parlier, M., Reznick, J. S., & Piven, J. (2007). The broad autism phenotype questionnaire. *Journal of Autism and Developmental Disorders, 37*(9), 1679-1690.

Insel, T., Cuthbert, B., Garvey, M., Heinssen, R., Pine, D. S., Quinn, K., . . . Wang, P. (2010). Research domain criteria (RDoC): toward a new classification framework for research on mental disorders: Am Psychiatric Assoc.

Jeste, S. S., Kirkham, N., Senturk, D., Hasenstab, K., Sugar, C., Kupelian, C., . . . Johnson, S. P. (2015). Electrophysiological evidence of heterogeneity in visual statistical learning in young children with ASD. *Developmental science, 18*(1), 90-105. doi: 10.1111/desc.12188

Jones, R. M., Tarpey, T., Hamo, A., Carberry, C., Brouwer, G., & Lord, C. (2018). Statistical Learning is Associated with Autism Symptoms and Verbal Abilities in Young Children with Autism. *Journal of Autism and Developmental Disorders*, 1-11.

Kidd, E. (2012). Implicit statistical learning is directly associated with the acquisition of syntax. *Developmental Psychology, 48*(1), 171-184. doi: http://dx.doi.org/10.1037/a0025405

Kidd, E., & Arciuli, J. (2016). Individual differences in statistical learning predict children's comprehension of syntax. *Child development*, *87*(1), 184-193. doi: http://dx.doi.org.proxy1.lib.uwo.ca/10.1111/cdev.12461

Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy: Evidence for a domain general learning mechanism. *Cognition, 83*(2), B35-B42. doi: http://dx.doi.org/10.1016/S0010-0277(02)00004-5

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.

Lany, J. (2014). Judging words by their covers and the company they keep: probabilistic cues support word learning. *Child development*, *85*(4), 1727-1739.

Lany, J., Shoaib, A., Thompson, A., & Estes, K. G. (2018). Infant statistical-learning ability is related to real-time language processing. *Journal of child language, 45*(2), 368-391.

Lieberman, M. D. (2000). Intuition: a social cognitive neuroscience approach. *Psychological bulletin*, *126*(1), 109.

Mayo, J., & Eigsti, I.-M. (2012). Brief report: A comparison of statistical learning in school-aged children with high functioning autism and typically developing peers. *Journal of Autism and Developmental Disorders*, *42*(11), 2476-2485. doi: http://dx.doi.org/10.1007/s10803-012-1493-0

Merzenich, M. M., Jenkins, W. M., Johnston, P., Schreiner, C., Miller, S. L., & Tallal, P. (1996). Temporal processing deficits of language-learning impaired children ameliorated by training. *Science, 271*(5245), 77-81.

A version of this paper is under review in *Scientific Reports* (Parks & Stevenson, *under review*).

Miller, G. A., & Selfridge, J. A. (1950). Verbal context and the recall of meaningful material. *The American Journal of Psychology, 63*, 176-185. doi: 10.2307/1418920

Misyak, J. B., & Christiansen, M. H. (2012). Statistical learning and language: An individual differences study. *Language Learning, 62*(1), 302-331. doi: http://dx.doi.org/10.1111/j.1467-9922.2010.00626.x

Newman, R., Ratner, N. B., Jusczyk, A. M., Jusczyk, P. W., & Dow, K. A. (2006). Infants' early ability to segment the conversational speech signal predicts later language development: a retrospective analysis. *Developmental Psychology*, *42*(4), 643.

Noel, J. P., De Niear, M. A., Stevenson, R., Alais, D., & Wallace, M. T. (2017). Atypical rapid audio-visual temporal recalibration in autism spectrum disorders. *Autism Research, 10*(1), 121-129.

Obeid, R., Brooks, P. J., Powers, K. L., Gillespie-Lynch, K., & Lum, J. A. G. (2016). Statistical learning in Specific Language Impairment and Autism Spectrum Disorder: A meta-analysis. *Frontiers in psychology*, *7*, 18.

Oram, J., Fine, J., Okamoto, C., & Tannock, R. (1999). Assessing the language of children with attention deficit hyperactivity disorder. *American Journal of Speech-Language Pathology*, *8*(1), 72-80.

Parks, K. M. A., & Stevenson, R. A. (2018). Auditory and Visual Statistical Learning are not Related to ADHD Symptomatology: Evidence from a Research Domain Criteria (RDoC) Approach. *Frontiers in psychology*, *9*, 2502.

Pellicano, E., & Burr, D. (2012). When the world becomes 'too real': A Bayesian explanation of autistic perception. *Trends in cognitive sciences, 16*(10), 504-510. doi: http://dx.doi.org.proxy1.lib.uwo.ca/10.1016/j.tics.2012.08.009

A version of this paper is under review in *Scientific Reports* (Parks & Stevenson, *under review*).

Pelucchi, B., Hay, J. F., & Saffran, J. R. (2009). Statistical Learning in a Natural Language by 8-Month-Old Infants. *Child development, 80*(3), 674-685.

Plaisted, K. C. (2015). Reduced generalization in autism: An alternative to weak central coherence.

Reber, A. S. (1967). Implicit learning of artificial grammars. *Journal of Verbal Learning & Verbal Behavior, 6*(6), 855-863. doi: http://dx.doi.org/10.1016/S0022-5371(67)80149-X

Robinson, C. C., Anderson, G. T., Porter, C. L., Hart, C. H., & Wouden-Miller, M. (2003). Sequential transition patterns of preschoolers' social interactions during child-initiated play: Is parallel-aware play a bidirectional bridge to other play states? *Early Childhood Research Quarterly, 18*(1), 3-21.

Romberg, A. R., & Saffran, J. R. (2010). Statistical learning and language acquisition. *Wiley Interdisciplinary Reviews: Cognitive Science, 1*(6), 906-914.

Roser, M. E., Aslin, R. N., McKenzie, R., Zahra, D., & Fiser, J. (2015). Enhanced visual statistical learning in adults with autism. *Neuropsychology, 29*(2), 163-172. doi: http://dx.doi.org.proxy1.lib.uwo.ca/10.1037/neu0000137

Saffran, Aslin, & Newport. (1996). Statistical learning by 8-month-old infants. *Science*, 1926-1928.

Saffran, Newport, & Aslin. (1996). Word segmentation: The role of distributional cues. *Journal of Memory and Language, 35*(4), 606-621.

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science (New York, N.Y.), 274*(5294), 1926-1928.

Saffran, J. R., Johnson, E. K., Aslin, R. N., & Newport, E. L. (1999). Statistical Learning of Tone Sequences by Human Infants and Adults. *Cognition, 70*(1), 27-52.

A version of this paper is under review in *Scientific Reports* (Parks & Stevenson, *under review*).

Saffran, J. R., Newport, E. L., & Aslin, R. N. (1996). Word segmentation: The role of distributional cues. *Journal of Memory and Language, 35*(4), 606-621.

Saffran, J. R., Newport, E. L., Aslin, R. N., Tunick, R. A., & Barrueco, S. (1997). Incidental language learning: Listening (and learning) out of the corner of your ear. *Psychological Science, 8*(2), 101-105. doi: http://dx.doi.org/10.1111/j.1467-9280.1997.tb00690.x

Saffran, J. R., Senghas, A., & Trueswell, J. C. (2001). The acquisition of language by children. *Proceedings of the National Academy of Sciences, 98*(23), 12874-12875.

Schapiro, A., & Turk-Browne, N. (2015). Statistical learning. *Brain mapping: An encyclopedic reference, 3*, 501-506.

Schapiro, A. C., Gregory, E., Landau, B., McCloskey, M., & Turk-Browne, N. B. (2014). The necessity of the medial temporal lobe for statistical learning. *Journal of Cognitive Neuroscience, 26*(8), 1736-1747. doi: http://dx.doi.org/10.1162/jocn_a_00578

Schapiro, A. C., Rogers, T. T., Cordova, N. I., Turk-Browne, N. B., & Botvinick, M. M. (2013). Neural representations of events arise from temporal community structure. *Nature neuroscience, 16*(4), 486.

Schapiro, A. C., Turk-Browne, N. B., Norman, K. A., & Botvinick, M. M. (2016). Statistical learning of temporal community structure in the hippocampus. *Hippocampus, 26*(1), 3-8. doi: http://dx.doi.org/10.1002/hipo.22523

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime: User's guide*: Psychology Software Incorporated.

Schulz, S. E., & Stevenson, R. A. (2018). Sensory hypersensitivity predicts repetitive behaviours in autistic and typically-developing children. *autism*, 1362361318774559.

A version of this paper is under review in *Scientific Reports* (Parks & Stevenson, *under review*).

Scott-Van Zeeland, A. A., McNealy, K., Wang, A. T., Sigman, M., Bookheimer, S. Y., & Dapretto, M. (2010). No Neural Evidence of Statistical Learning During Exposure to Artificial Languages in Children with Autism Spectrum Disorders. *Biological Psychiatry, 68*(4), 345-351. doi: 10.1016/j.biopsych.2010.01.011

Siegelman, N., Bogaerts, L., & Frost, R. (2016). Measuring individual differences in statistical learning: Current pitfalls and possible solutions. *Behavior Research Methods, 49*(2), 418-432. doi: http://dx.doi.org/10.3758/s13428-016-0719-z

Siegelman, N., & Frost, R. (2015). Statistical learning as an individual ability: Theoretical perspectives and empirical evidence. *Journal of Memory and Language, 81*, 105-120. doi: http://dx.doi.org/10.1016/j.jml.2015.02.001

Smith, G. N., Conway, C. M., Bauernschmidt, A., & Pisoni, D. B. (2015). Can we improve structured sequence processing? Exploring the direct and indirect effects of computerized training using a mediational model. *PloS one*, *10*(5), e0127148.

Stevenson, R. A., Baum, S. H., Segers, M., Ferber, S., Barense, M. D., & Wallace, M. T. (2017). Multisensory speech perception in autism spectrum disorder: From phoneme to whole-word perception. *Autism Research, 10*(7), 1280-1290.

Stevenson, R. A., Sun, S. Z., Hazlett, N., Cant, J. S., Barense, M. D., & Ferber, S. (2016). Seeing the forest and the trees: default local processing in individuals with high autistic traits does not come at the expense of global attention. *Journal of Autism and Developmental Disorders*, 1-15.

Stevenson, R. A., Toulmin, J. K., Youm, A., Besney, R. M., Schulz, S. E., Barense, M. D., & Ferber, S. (2017). Increases in the autistic trait of attention to detail are associated with decreased multisensory temporal adaptation. *Scientific reports, 7*(1), 14354.

A version of this paper is under review in *Scientific Reports* (Parks & Stevenson, *under review*).

Toro, J. M., Sinnett, S., & Soto-Faraco, S. (2005). Speech segmentation by statistical learning depends on attention. *Cognition, 97*(2), B25-B34.

Wiig, E. H., Semel, E. M., Secord, W., & Pearson Education, I. (2013). *CELF-5: Clinical Evaluation of Language Fundamentals*. Bloomington, MN: Pearson.

Yager, J., & Iarocci, G. (2013). The development of the multidimensional social competence scale: A standardized measure of social competence in autism spectrum disorders. *Autism Research, 6*(6), 631-641.

A version of this paper is under review in *Scientific Reports* (Parks & Stevenson, *under review*).

Chapter 3

3 Experiment II – Auditory and Visual Statistical Learning are not Related to ADHD Symptomatology: Evidence from a Research Domain Criteria (RDoC) Approach

Similar events and pieces of information tend to co-occur reliably within the environment. The ability to identify and predict these statistical relationships in the environment is a process referred to as statistical learning. Extracting such probabilistic information is important for individuals to make sense of their world and has been shown to play a role in both language proficiency (Kidd, 2012) and predicting behavioural patterns (Baldwin et al., 2008). Statistical learning is an implicit mechanism that requires learners to process rapid and continuous transitions in sensory input. Individuals are able to learn patterns and regularities without explicit instruction or awareness (Reber, 1967). The ability to track and predict statistical patterns has been observed across many types of tasks and stimuli, including visual stimuli (Kirkham et al., 2002), tactile stimuli (Conway and Christiansen, 2005), non-linguistic sounds (Gebhart et al., 2009), auditory syllables (Saffran et al., 1996;Saffran et al., 1999), and within scenes and in response to body movements (Baldwin et al., 2008).

Statistical learning has been explored in both children and adults with attention-deficit/hyperactivity disorder (ADHD) to test the hypothesis that impairments in statistical learning may contribute to ADHD traits. Many of these studies have used an implicit sequence learning task known as the serial reaction time task (SRT). During this task, participants are required to respond to a set of stimuli that follows a repeating pattern that they should learn to predict with repeated exposure, assuming their statistical learning skills are intact. However,

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among the studies using the SRT with individuals with ADHD, findings have been inconsistent, with some studies reporting intact (Karatekin et al., 2009;Vloet et al., 2010;Takács et al., 2017;Pedersen and Ohrmann, 2018), and others reporting atypical learning relative to TD peers (Klorman et al., 2002;Barnes et al., 2010). Despite these findings, there is evidence to suggest that the ability to learn implicit patterns is impaired outside of traditional SRT tasks, suggesting that SRT tasks may fall short in capturing impairments. For instance, impaired statistical learning has been reported in preschoolers with ADHD when an artificial grammar task was used (Domuta and Pentek, 2003) and individuals with ADHD also tend to have difficulties arranging or sequencing information in a way that is logical and cohesive (Purvis and Tannock, 1997). One possible limitation to using the SRT task to measure implicit sequence learning is that only response time is used as an index of learning (Moisello et al., 2009), making it difficult to disentangle implicit and explicit processes. To test whether statistical learning abilities outside of the SRT task relate to ADHD traits, we used well-established auditory and visual statistical learning paradigms which have the benefit of reliably assessing implicit learning through the collection of accuracy scores.

Given the apparent difficulties with statistical learning in ADHD, we hypothesize that:

1) ADHD traits will be inversely related to auditory and visual statistical learning abilities and,
2) Given that inattention and hyperactivity are characterized as distinct behavioural symptoms in ADHD, we predict that inattention and hyperactivity will uniquely contribute to statistical learning abilities.

3.1 Materials and Methods

Participants included 104 young adults recruited from the undergraduate psychology pool at the University of Western Ontario as part of a larger study on developmental disabilities. Six participants were excluded, five for being over the maximum age for which the standardized language measure intended, and one for failure to complete the protocol, resulting in a final sample of 98 participants aged 16-21 years (*Mean age* = 18.19, *SD* = .74 years, 64.3% female). Participants were recruited based upon the Research Domain Criteria (RDoC) framework in order to cover the entire range of traits (Insel et al., 2010;Cuthbert and Insel, 2013), and thus were not required to have a formal ADHD diagnosis. All participants were English speaking and had self-reported normal or corrected-to-normal vision and normal hearing. All protocols were approved by the University of Western Ontario Research Ethics Board.

3.1.1 Auditory Statistical Language Learning Paradigm

Participants completed a well-established auditory statistical learning task similar to that described in the study by Saffran et al. (1997). Participants first completed a language exposure phase where they were exposed to a structured, unsegmented language stream for 21 minutes. The language consisted of six tri-syllabic nonsense "words": *tutibu, babupu, bupada, pidadi, patubi, and dutaba.* There were no acoustic markers to indicate word boundaries between words. However, within the language stream, there were higher transitional probabilities within words (1.0 or 0.33) than between words (0.1 or 0.2), where transitional probabilities were calculated as:

$$p(Y|X) = \frac{p(X \cap Y)}{p(X)}$$

Immediately following the artificial language exposure, participants completed a two-alternative forced-choice test (2AFC) to assess whether they could identify trained words from the artificial language (see appendix H for supplemental materials for auditory and visual statistical learning trial details).

3.1.2 Visual Statistical Learning Paradigm

Participants then completed a visual statistical learning task identical to that used by Siegelman, Bogaerts, and Frost (2016). Similar to the auditory task, the visual task was comprised of both a learning phase and a test phase where transitional probabilities were higher for within-shape sequences than between **(Figure 6)**. The shapes were organized into eight triplets that differed according to their within-triplet transitional probabilities, with four triplet items having transitional probabilities of 0.33 and the other four having transitional probabilities of 1.0. Between-triplet transitional probabilities were .14 or less. In the 42-item test phase, the first block of 34 four trials were pattern recognition items and required participants to pick the familiar sequence from either two (2AFC) or four (4AFC) possible responses. The next eight trials were pattern completion items where participants were instructed to select the shape that best completed the sequence.

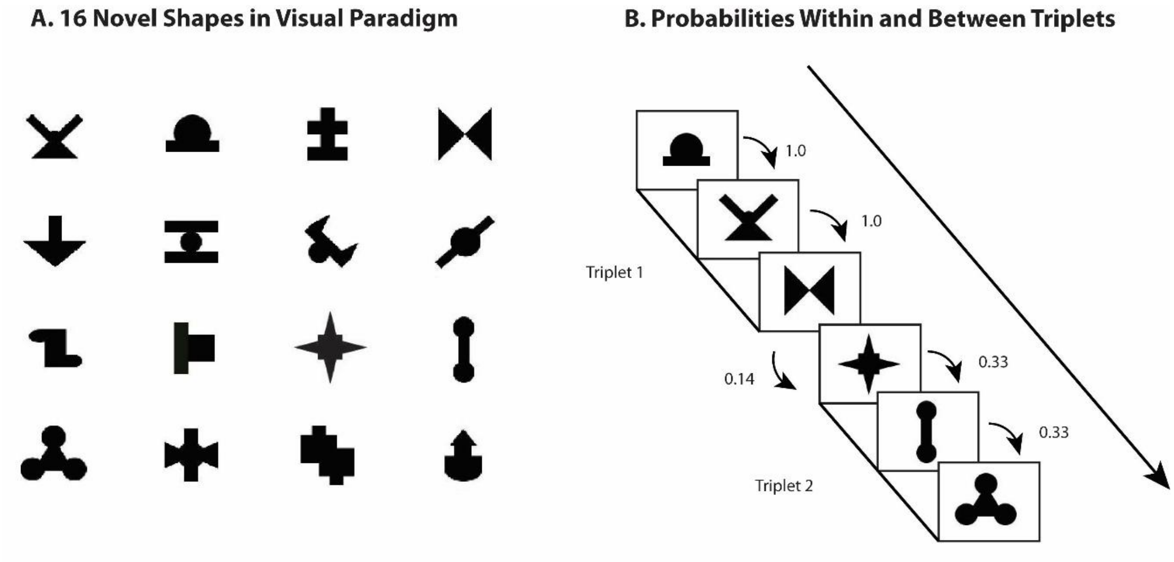

Figure 6: (A) 16 novel shapes used in visual paradigm (B) example of probabilities within and between triplets.

3.1.3 Standardized Measure of ADHD Traits

The Adult ADHD Self-Report Scale (ASRS-v1.1; Kessler et al., 2005) was used to measure participants' ADHD symptoms. On this 18-item measure, participants responded on a five-point Likert scale to reflect the frequency with which they experienced challenges with inattention and/or hyperactivity. The ASRS was chosen for the current study because it is a reliable screening measure that has been shown to be successful in screening for ADHD characteristics in the general population where no formal diagnosis of ADHD has been reported (Kessler et al., 2005;Kessler et al., 2007).

3.1.4 Analysis

Participants' mean accuracy scores were calculated for both statistical learning paradigms and t-tests were conducted to compare accuracy scores to chance levels to ensure that statistical learning occurred. ADHD traits were quantified by scoring participants' responses for each of the 18-items of the ASRS as "0" or "1" in accordance with Kessler et al. (2005) to derive a total score (sum of scores across all 18 items), and scores for inattention (sum of items tapping inattention) and hyperactivity (sum of items tapping hyperactivity).

Bivariate Bayesian correlations (JASP, 2018) were then used to examine relationships between ADHD symptoms and statistical learning with a Benjamini-Hochberg false discovery rate procedure (Q=.1) used to correct for multiple comparisons. Bayesian linear regressions were also used to examine whether inattention and hyperactivity uniquely contributed to statistical learning.

3.2 Results

Scores on the ASRS confirmed that the sample spanned nearly the entire range of traits, (0-17 out of a possible 0-18) in line with the RDoC framework. Previous standardization of the ASRS identified scores of 0-10/11-18 as the best split point predicting clinical-level symptoms with a classification accuracy of 96.2% (specificity = 98.3%, sensitivity 56.3%) (Kessler et al., 2007). The current sample included 16 participants (16.33%) scoring at levels considered at risk for ADHD.

Above chance performance on statistical learning tasks were examined and found to be reliability above chance for both auditory (mean accuracy=64%, $t_{(97)}$=58.53, p<.001, d=5.82) and visual (mean accuracy=58%, $t_{(97)}$=42.07, p<.001, d=4.14) statistical learning tasks.

Contrary to our predictions, auditory and visual statistical learning were not significantly related to overall ADHD traits ($r_{(97)}$=-.02, p=.849, BF_{10}=.129, and $r_{(97)}$=-.01 p=.908, BF_{10}=.127, respectively). Further, when isolating inattention versus hyperactivity-impulsivity characteristics of ADHD, neither inattention ($r_{(97)}$=.02, p=.816, BF_{10}=.130; $r_{(97)}$=.02, p=.871, BF_{10}=.128) nor hyperactivity ($r_{(97)}$=-.06, p=.529, BF_{10}=.154; $r_{(97)}$=-.04, p=.683, BF_{10}=.137) scores significantly related to auditory or visual statistical learning, respectively **(Figure 7)**. To determine whether inattention and hyperactivity uniquely contributed to auditory statistical learning, a multiple regression was performed, and the overall model was not significant, $F_{(2,95)}$=.417, *p*=.660, R^2=.01, BF_{10} = .095. When isolated, neither inattention (β=.003, $t_{(95)}$=.66, *p*=.510, sr^2=.005, BF_{10}= .218) nor hyperactivity (β=-.005, $t_{(95)}$=-.88, *p*=.379, sr^2=.008, BF_{10}= .254) were statistically significant in this model. A second multiple regression was performed to determine if inattention and hyperactivity uniquely contributed to visual statistical learning and the overall model was not significant, $F_{(2,95)}$=.181, *p*=.835, R^2=.004, BF_{10}=.078. When isolated, both inattention (β=.003, $t_{(95)}$=.44, *p*=.659, sr^2=.002, BF_{10}=.215) and hyperactivity (β=-.004, $t_{(95)}$=-.58, *p*=.564, sr^2=0.003, BF_{10}=.229) were not statistically significant in this model.

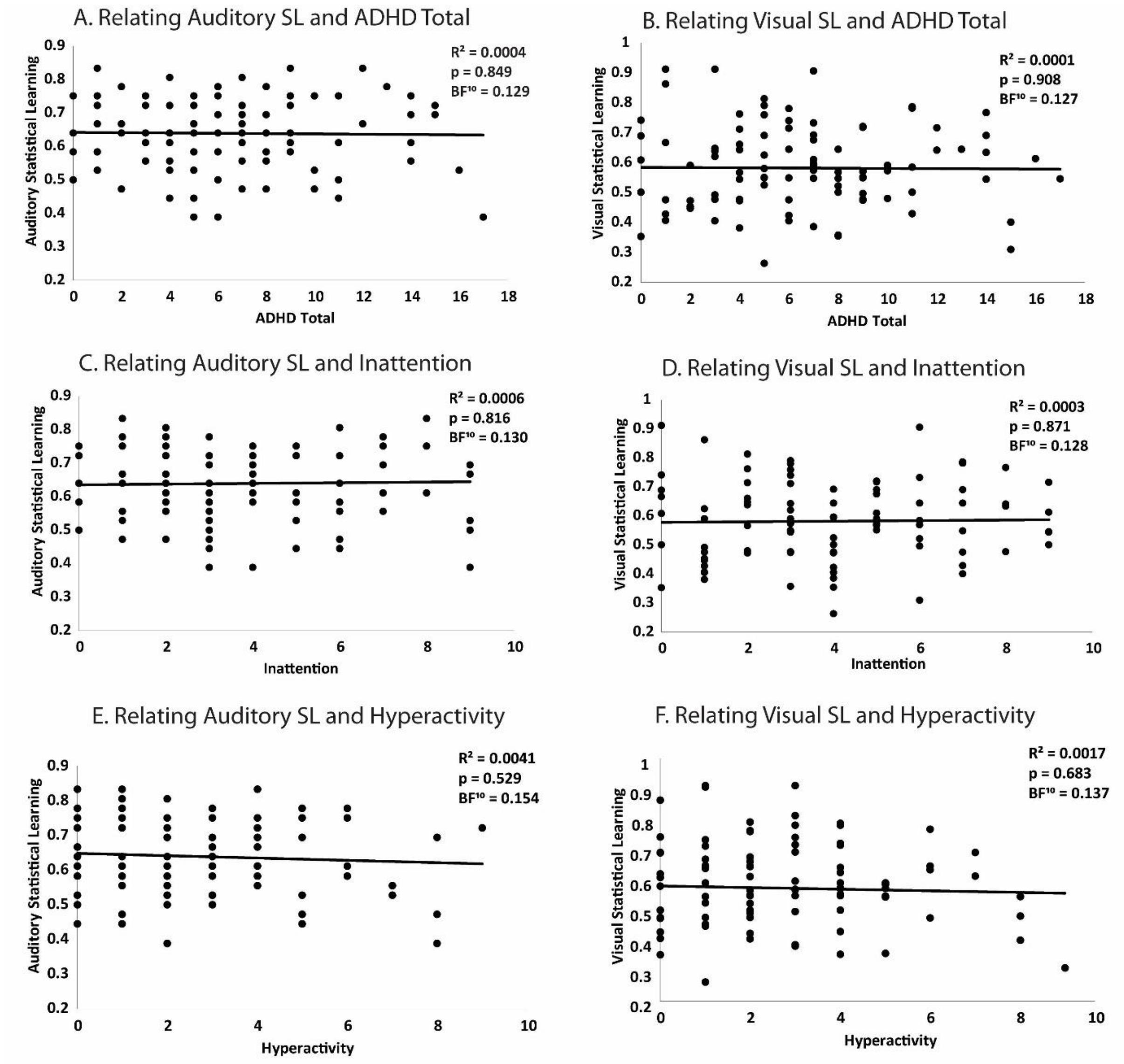

Figure 7: Relating (A) auditory statistical learning and total ADHD traits (B) visual statistical learning and total ADHD traits (C) auditory statistical learning and inattention (D) visual statistical learning and inattention (E) auditory statistical learning and hyperactivity (F) visual statistical learning and hyperactivity.

3.3 Discussion

Although our hypotheses surrounding ADHD traits and statistical learning were not supported by the data, past research on this topic has been mixed, with a number of studies suggesting that individuals with ADHD exhibit impaired statistical learning abilities (Klorman et al., 2002;Domuta and Pentek, 2003;Barnes et al., 2010;Sakreida, 2011). Here, we hypothesized that individuals with higher ADHD traits would show decreased statistical learning abilities however, we did not find any evidence to support a relationship between ADHD symptoms and statistical learning.

It is notable that despite using a variety of tasks to assess statistical learning, a number of studies have found this ability to be unimpaired in ADHD, suggesting that similar results would emerge if a clinical sample was included in the current study. Despite this, there is evidence to suggest that statistical learning may be impaired in ADHD, including impairments in executive functioning (Willcutt et al., 2005) and abnormalities in the brain structures that underlie the implicit memory system, such as the frontal and basal-ganglia networks (Cubillo et al., 2012). This system is particularly important for processing sequences and predicting probabilistic outcomes within these sequences (Takács et al., 2017). Indeed, children with ADHD have been shown to be less sensitive at the neural level to violations in sequences that follow a probabilistic structure (Klorman et al., 2002). Finally, it has been hypothesized that the neural circuits responsible for predicting probabilistic cues in the environment including *what* (frontostriatal) may occur and *when* (frontoneocerebellar) that event may occur are both impaired in ADHD, resulting in less accurate expectations about the environment as well as a weakened ability to detect violations and adjust one's behaviour according to these violations (Nigg and Casey, 2005).

Prior studies failing to find a significant link between statistical learning and ADHD symptoms, however, have been limited in that common frequentist hypothesis testing is unable to provide direct support for a null hypothesis. Our Bayesian analyses provide novel evidence directly supporting the hypothesis that ADHD traits and statistical learning are decoupled, at least in individuals who do not have a formal diagnosis of ADHD. This finding held for overall levels of ADHD traits as well as the subdomains of inattention and hyperactivity. These null findings are important for informing future studies that intend to assess if/how this ability relates to ADHD and related symptoms.

There are several important considerations for future work. First, future studies exploring the possible relationship between ADHD traits and statistical learning should include child participants to determine whether the relations differ in younger populations. Previous work examining statistical learning in children with ADHD has found this ability to be impaired (Domuta and Pentek, 2003). Further, the majority of research examining statistical learning abilities in typical development has focused on child populations (Newman et al., 2006;Kidd, 2012;Ellis et al., 2014;Kidd and Arciuli, 2016). It is therefore possible that the ability to learn these patterns is more prominent in the early years. Second, future research should examine whether the ability to learn more complex sequencing relationships that involve non-adjacent dependencies is impaired in ADHD. Finally, an RDoC approach should be applied to future work to examine the entire spectrum of levels of ADHD traits. Online recruitment platforms, such as Amazon Mechanical Turk can help researchers achieve this goal by reaching a more representative population with a distribution of symptoms across a continuous spectrum of ADHD (Crump et al., 2013).

3.4 References

Baldwin, D., Andersson, A., Saffran, J., and Meyer, M. (2008). Segmenting dynamic human action via statistical structure. *Cognition* 106**,** 1382-1407.

Barnes, K.A., Howard Jr, J.H., Howard, D.V., Kenealy, L., and Vaidya, C.J. (2010). Two forms of implicit learning in childhood ADHD. *Developmental neuropsychology* 35**,** 494-505.

Conway, C.M., and Christiansen, M.H. (2005). Modality-constrained statistical learning of tactile, visual, and auditory sequences. *Journal of experimental psychology. Learning, memory, and cognition* 31**,** 24-39.

Crump, M.J., Mcdonnell, J.V., and Gureckis, T.M. (2013). Evaluating Amazon's Mechanical Turk as a tool for experimental behavioral research. *PloS one* 8**,** e57410.

Cubillo, A., Halari, R., Smith, A., Taylor, E., and Rubia, K. (2012). A review of fronto-striatal and fronto-cortical brain abnormalities in children and adults with Attention Deficit Hyperactivity Disorder (ADHD) and new evidence for dysfunction in adults with ADHD during motivation and attention. *cortex* 48**,** 194-215.

Cuthbert, B.N., and Insel, T.R. (2013). Toward the future of psychiatric diagnosis: the seven pillars of RDoC. *BMC medicine* 11**,** 126.

Domuta, A., and Pentek, I. (2003). Implicit learning in ADHD preschool children. *Implicit learning in ADHD preschool children*.

Ellis, E.M., Gonzalez, M.R., and Deák, G.O. (2014). Visual prediction in infancy: What is the association with later vocabulary? *Language Learning and Development* 10**,** 36-50.

Gebhart, A.L., Newport, E.L., and Aslin, R.N. (2009). Statistical learning of adjacent and nonadjacent dependencies among nonlinguistic sounds. *Psychonomic bulletin & review* 16**,** 486-490.

Insel, T., Cuthbert, B., Garvey, M., Heinssen, R., Pine, D.S., Quinn, K., Sanislow, C., and Wang, P. (2010). "Research domain criteria (RDoC): toward a new classification framework for research on mental disorders". Am Psychiatric Assoc).

Karatekin, C., White, T., and Bingham, C. (2009). Incidental and intentional sequence learning in youth-onset psychosis and attention-deficit/hyperactivity disorder (ADHD). *Neuropsychology* 23**,** 445.

Kessler, R.C., Adler, L., Ames, M., Demler, O., Faraone, S., Hiripi, E., Howes, M.J., Jin, R., Secnik, K., and Spencer, T. (2005). The World Health Organization Adult ADHD Self-Report Scale (ASRS): a short screening scale for use in the general population. *Psychological medicine* 35**,** 245-256.

Kessler, R.C., Adler, L.A., Gruber, M.J., Sarawate, C.A., Spencer, T., and Van Brunt, D.L. (2007). Validity of the World Health Organization Adult ADHD Self-Report Scale (ASRS) Screener in a representative sample of health plan members. *International journal of methods in psychiatric research* 16**,** 52-65.

Kidd, E. (2012). Implicit statistical learning is directly associated with the acquisition of syntax. *Developmental Psychology* 48**,** 171-184.

Kidd, E., and Arciuli, J. (2016). Individual differences in statistical learning predict children's comprehension of syntax. *Child Development* 87**,** 184-193.

Kirkham, N.Z., Slemmer, J.A., and Johnson, S.P. (2002). Visual statistical learning in infancy: Evidence for a domain general learning mechanism. *Cognition* 83**,** B35-B42.

Klorman, R., Thatcher, J.E., Shaywitz, S.E., Fletcher, J.M., Marchione, K.E., Holahan, J.M., Stuebing, K.K., and Shaywitz, B.A. (2002). Effects of event probability and sequence on children with attention-deficit/hyperactivity, reading, and math disorder. *Biological Psychiatry* 52**,** 795-804.

Moisello, C., Crupi, D., Tunik, E., Quartarone, A., Bove, M., Tononi, G., and Ghilardi, M.F. (2009). The serial reaction time task revisited: a study on motor sequence learning with an arm-reaching task. *Experimental brain research* 194**,** 143-155.

Newman, R., Ratner, N.B., Jusczyk, A.M., Jusczyk, P.W., and Dow, K.A. (2006). Infants' early ability to segment the conversational speech signal predicts later language development: a retrospective analysis. *Developmental psychology* 42**,** 643.

Nigg, J.T., and Casey, B. (2005). An integrative theory of attention-deficit/hyperactivity disorder based on the cognitive and affective neurosciences. *Development and psychopathology* 17**,** 785-806.

Pedersen, A., and Ohrmann, P. (2018). Impaired behavioral inhibition in implicit sequence learning in adult ADHD. *Journal of attention disorders* 22**,** 250-260.

Purvis, K.L., and Tannock, R. (1997). Language abilities in children with attention deficit hyperactivity disorder, reading disabilities, and normal controls. *Journal of Abnormal Child Psychology* 25**,** 133-144.

Reber, A.S. (1967). Implicit learning of artificial grammars. *Journal of Verbal Learning & Verbal Behavior* 6**,** 855-863.

Saffran, Aslin, and Newport (1996). Statistical learning by 8-month-old infants. *Science***,** 1926-1928.

Saffran, J.R., Johnson, E.K., Aslin, R.N., and Newport, E.L. (1999). Statistical learning of tone sequences by human infants and adults. *Cognition* 70**,** 27-52.

Saffran, J.R., Newport, E.L., Aslin, R.N., Tunick, R.A., and Barrueco, S. (1997). Incidental language learning: Listening (and learning) out of the corner of your ear. *Psychological Science* 8**,** 101-105.

Sakreida, K. (2011). Neuropsychologie und neuronale Grundlagen der ADHS. *Psychotherapie im Dialog* 12**,** 238.

Siegelman, N., Bogaerts, L., and Frost, R. (2016). Measuring individual differences in statistical learning: Current pitfalls and possible solutions. *Behavior Research Methods* 49**,** 418-432.

Takács, Á., Shilon, Y., Janacsek, K., Kóbor, A., Tremblay, A., Németh, D., and Ullman, M.T. (2017). Procedural learning in Tourette syndrome, ADHD, and comorbid Tourette-ADHD: Evidence from a probabilistic sequence learning task. *Brain and Cognition* 117**,** 33-40.

Vloet, T.D., Marx, I., Kahraman-Lanzerath, B., Zepf, F.D., Herpertz-Dahlmann, B., and Konrad, K. (2010). Neurocognitive performance in children with ADHD and OCD. *Journal of Abnormal Child Psychology* 38**,** 961-969.

Willcutt, E.G., Doyle, A.E., Nigg, J.T., Faraone, S.V., and Pennington, B.F. (2005). Validity of the executive function theory of attention-deficit/hyperactivity disorder: a meta-analytic review. *Biological psychiatry* 57**,** 1336-1346.

4 Discussion

The aim of the current project was to examine whether auditory and visual statistical learning abilities relate to ASD and ADHD traits in an attempt to examine whether a decreased ability to learn such patterns relates to increased ASD and ADHD traits. Further, it was of interest to investigate whether these decreased abilities would relate to decreased language and social communication abilities in both groups.

Results from Study 1 demonstrated that visual statistical learning plays an important role in language and social competency abilities. More specifically, the relationship between visual statistical learning and social competency was mediated by language comprehension abilities, suggesting that impairments in statistical learning may cascade into impairments in language which then impacts social competency. These findings are consistent with prior work, showing that statistical learning is atypical in ASD and that this ability is related to level of communicative impairments (Scott-Van Zeeland et al., 2010) social functioning (Jeste et al., 2015), and verbal abilities (Jones et al., 2018). While the cascading impact of visual statistical learning into associated issues with language and social competency align well with ASD traits and previous research, it should be noted here that auditory, but *not* visual statistical learning was related to autistic traits.

There are a number of distinct possible reasons for this discrepancy. First, although previous behavioural studies have failed to show a deficit in visual statistical learning (Roser, Aslin, McKenzie, Zahra, & Fiser, 2015), neural findings have demonstrated atypical statistical learning in ASD (Jeste, et al., 2015), suggesting that this atypical processing might only be apparent through the use of neural-based measures. It may also be that individuals with autism are able to compensate for this deficit behaviourally, and therefore show similar performance to TD individuals in such tasks. Second, no behavioural studies, to our knowledge, have examined the relationship between statistical learning and autism symptom severity. Instead, studies often confirm diagnosis using the Autism Diagnostic Interview, Autism Diagnostic Observation Schedule, or Autism Spectrum Quotient while failing to account for potential relationships between these measures and statistical learning abilities. Previous studies have also only compared clinical samples of ASD to well-matched TD controls rather than comparing visual statistical learning to traits within ASD samples. Third, there is considerable heterogeneity in ASD and this variability extends to accompanying language, social skills, and autistic traits themselves. This is the first study to examine whether statistical learning is related to autistic traits using an RDoC framework. Our failure to find a relationship between visual statistical learning and autistic traits could be explained by having a restricted range of language and social deficits, and level of autistic traits relative to clinical samples that have been used in previous work. Even with these possibilities, the relationship between visual statistical learning, language, and social competence suggest that training related to improving visual statistical learning abilities may prove a useful tool in optimizing language and social outcomes in ASD.

There are a number of possible explanations for our divergent findings between auditory and visual statistical learning and how these related to traits, language, and social competency. First, our finding that only auditory statistical learning was related to autistic traits may be the result of enhanced visual processing in ASD where studies have shown that autistic individuals demonstrate similar or superior visual processing abilities compared to TD individuals (Bertone, Mottron, Jelenic, & Faubert, 2005; Caron, Mottron, Berthiaume, & Dawson, 2006). It may also be that since our statistical learning tasks were not matched, the visual task was able to tap into more complex abilities that relate more closely to higher-level language and social processing and this may explain why visual, but not auditory statistical learning was related to language and social competency. For example, the visual task included pattern completion trials which may be useful for understanding appropriate ordering in sentence structure or social interactions. We initially chose to use these two divergent paradigms to replicate previous statistical learning paradigms and make our findings comparable to that of previous research, however, future studies are needed in which the auditory and visual paradigms are well matched.

Conversely, results from Study 2 indicated that ADHD traits were not related to auditory and visual statistical learning. An identical pattern emerged when inattention and hyperactivity components were separated, indicating that neither of these distinct behavioural symptoms of ADHD are related to statistical learning abilities. These findings converge with other studies but go beyond findings a lack of a significant relationship – through Bayesian analyses, these data provide novel evidence directly supporting the hypothesis that ADHD traits and statistical learning are decoupled. This finding held for overall levels of ADHD traits as well as subdomains of inattention and hyperactivity, suggesting that the ability to pick up on patterns in both auditory and visual domains is intact in ADHD. Future work should consider investigating statistical learning in ADHD across ages to determine whether this ability is more closely related to language and social outcomes in younger populations, as well as move beyond auditory and visual domains.

4.1 Implications

The current study examined ASD and ADHD traits using a RDoC framework where symptoms are classified as varying in severity across a continuum (Cuthbert, 2014; Insel et al., 2010). Through this dimensional approach, a better understanding of the mechanisms underlying a symptom or group of symptoms that often manifest at sub-clinical levels can be measured across diagnoses and within the general population to determine the amount of convergence and divergence occurring across groups. In turn, researchers can incorporate larger sample sizes, allowing for correlation studies that often require a large sample, as oppose to split-group studies. The application of this dimensional approach can also increase task accessibility so that different abilities can be measured across a variety of tasks that might otherwise be too attentionally or cognitively demanding for autistic individuals and individuals with ADHD. Examining ASD and ADHD traits in the general population may therefore have the potential to inform new therapies and intervention techniques aimed at remediating symptom related difficulties. Here, we have demonstrated that these traits are apparent in individuals without a formal diagnosis and that past findings using clinical samples can be replicated through this RDoC framework, providing a promising direction for future studies investigating links between statistical learning, language, and social functioning in non-clinical samples.

Our results also highlight the need to push toward complimentary classification approaches in research that can provide useful ways of examining a range of disorders and that therapies should be tailored to account for the spectrum of traits in developmental disorders such as ASD and ADHD. Importantly, our findings suggest that implementing pattern learning approaches early on in classroom and home environments may help to limit the presentation of language and social difficulties associated with ASD.

4.2 Future Directions

Given the amount of heterogeneity in ASD and ADHD, individual differences in statistical learning abilities should be the focus of future research. Interventions can then be tailored to suit individual learning abilities, with the goal of increasing language and social outcomes, at least in ASD. Further, statistical learning is a process that occurs continuously and incrementally and therefore, measures of statistical learning should be adapted to quantify the complexity of this learning (Siegelman, Bogaerts, Kronenfeld, & Frost, 2018). Also, well-established 2AFC tasks are not suitable for implementation in individuals with cognitive-impairments (i.e. low-functioning ASD). These problems can be addressed by looking at learning online, while it is occurring (Schapiro, Rogers, Cordova, Turk-Browne, & Botvinick, 2013; Schapiro, Turk-Browne, Norman, & Botvinick, 2016) using a temporal community structure approach, as well as through the use of neural-based measures (Batterink & Paller, 2017; Jeste, et al., 2015). These methods measure statistical learning passively, allowing researchers to translate similar paradigms into lower-functioning populations that have been historically underserved in research. Findings from such studies may provide additional insight into *how* patterns of information are being formed early on in typical development and how this may differ across developmental disabilities with the aim of designing interventions that target the needs of specific disorders.

It may also be of interest to investigate the consolidation of statistical learning and how adaptive these abilities are. For example, examining whether participants are able to pick up on probability changes between syllables or shapes and if so, how fast they are able to identify these changes. The predictive coding hypothesis argues that atypical processing in ASD may be explained by a weakened ability to rely on prior information or experiences to inform perception

(Pellicano & Burr, 2012; Van Boxtel & Lu, 2013) and may provide support for a decreased ability to detect such probabilistic changes in ASD.

Another potential avenue for statistical learning research involves looking at the ability to integrate information from two senses (multisensory integration; Stevenson, Ghose, et al., 2014), to determine whether learners show greater benefits of learning when auditory and visual information (i.e. highly predictable syllable and shape pairings) are presented simultaneously (Altieri, Stevenson, Wallace, & Wenger, 2015). Prior studies have demonstrated difficulties related to combining auditory and visual information in ASD (Baum, Stevenson, & Wallace, 2015a, 2015b; Donohue, Darling, & Mitroff, 2012; Noel, De Niear, Stevenson, Alais, & Wallace, 2017; Noel, Stevenson, & Wallace, 2018; Stevenson et al., 2017; Stevenson et al., 2015; Stevenson et al., 2018; Stevenson, Siemann, Schneider, et al., 2014; Stevenson, Siemann, Woynaroski, et al., 2014a, 2014b; Wallace & Stevenson, 2014; Woynaroski et al., 2013) and ADHD (Panagiotidi, Overton, & Stafford, 2017; Shimizu, Bueno, & Miranda, 2014), and it is therefore expected that these individuals would show reduced benefits when presented with information from multiple sensory modalities relative to TD individuals. The ability to combine information from multiple senses is particularly important for language and social functioning given that visual articulations are always matched with particular speech sounds in the environment. Indeed, previous studies have shown that atypical sensory abilities in autism have a cascading impact on the integration of multisensory social information and speech perception (Stevenson, et al., 2017; Stevenson, Segers, Ferber, Barense, & Wallace, 2014; Stevenson, et al., 2018) Thus, examining the potential impact of multisensory statistical learning on language and social communication in ASD and other developmental disabilities may help to inform remediation strategies.

4.4 References

Altieri, N., Stevenson, R. A., Wallace, M. T., & Wenger, M. J. (2015). Learning to associate auditory and visual stimuli: behavioral and neural mechanisms. *Brain Topogr*, *28*(3), 479-493. doi: 10.1007/s10548-013-0333-7

Batterink, L. J., & Paller, K. A. (2017). Online neural monitoring of statistical learning. *cortex, 90*, 31-45.

Baum, S. H., Stevenson, R. A., & Wallace, M. T. (2015a). Behavioral, perceptual, and neural alterations in sensory and multisensory function in autism spectrum disorder. *Prog Neurobiol*, *134*, 140-160. doi: 10.1016/j.pneurobio.2015.09.007

Baum, S. H., Stevenson, R. A., & Wallace, M. T. (2015b). Testing sensory and multisensory function in children with autism spectrum disorder. *J Vis Exp*(98), e52677. doi: 10.3791/52677

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

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

Cuthbert, B. N. (2014). The RDoC framework: facilitating transition from ICD/DSM to dimensional approaches that integrate neuroscience and psychopathology. *World Psychiatry*, *13*(1), 28-35.

Donohue, S. E., Darling, E. F., & Mitroff, S. R. (2012). Links between multisensory processing and autism. [journal article]. *Experimental Brain Research, 222*(4), 377-387. doi: 10.1007/s00221-012-3223-4

Insel, T., Cuthbert, B., Garvey, M., Heinssen, R., Pine, D. S., Quinn, K., . . . Wang, P. (2010). Research domain criteria (RDoC): toward a new classification framework for research on mental disorders: Am Psychiatric Assoc.

Jeste, S. S., Kirkham, N., Senturk, D., Hasenstab, K., Sugar, C., Kupelian, C., . . . Johnson, S. P. (2015). Electrophysiological evidence of heterogeneity in visual statistical learning in young children with ASD. *Developmental Science, 18*(1), 90-105. doi: 10.1111/desc.12188

Jones, R. M., Tarpey, T., Hamo, A., Carberry, C., Brouwer, G., & Lord, C. (2018). Statistical Learning is Associated with Autism Symptoms and Verbal Abilities in Young Children with Autism. *Journal of autism and developmental disorders*, 1-11.

Noel, J. P., De Niear, M. A., Stevenson, R., Alais, D., & Wallace, M. T. (2017). Atypical rapid audio-visual temporal recalibration in autism spectrum disorders. *Autism Research, 10*(1), 121-129.

Noel, J. P., Stevenson, R. A., & Wallace, M. T. (2018). Atypical audiovisual temporal function in autism and schizophrenia: similar phenotype, different cause. *European Journal of Neuroscience, 47*(10), 1230-1241.

Panagiotidi, M., Overton, P. G., & Stafford, T. (2017). Multisensory integration and ADHD-like traits: evidence for an abnormal temporal integration window in ADHD. *Acta psychologica, 181*, 10-17.

Pellicano, E., & Burr, D. (2012). When the world becomes 'too real': a Bayesian explanation of autistic perception. *Trends in cognitive sciences, 16*(10), 504-510.

Roser, M. E., Aslin, R. N., McKenzie, R., Zahra, D., & Fiser, J. (2015). Enhanced visual statistical learning in adults with autism. *Neuropsychology, 29*(2), 163-172. doi: http://dx.doi.org.proxy1.lib.uwo.ca/10.1037/neu0000137

Schapiro, A. C., Rogers, T. T., Cordova, N. I., Turk-Browne, N. B., & Botvinick, M. M. (2013). Neural representations of events arise from temporal community structure. *Nature neuroscience, 16*(4), 486.

Schapiro, A. C., Turk-Browne, N. B., Norman, K. A., & Botvinick, M. M. (2016). Statistical learning of temporal community structure in the hippocampus. *Hippocampus, 26*(1), 3-8.

Scott-Van Zeeland, A. A., McNealy, K., Wang, A. T., Sigman, M., Bookheimer, S. Y., & Dapretto, M. (2010). No Neural Evidence of Statistical Learning During Exposure to Artificial Languages in Children with Autism Spectrum Disorders. *Biological Psychiatry, 68*(4), 345-351. doi: 10.1016/j.biopsych.2010.01.011

Shimizu, V. T., Bueno, O. F., & Miranda, M. C. (2014). Sensory processing abilities of children with ADHD. *Brazilian journal of physical therapy, 18*(4), 343-352.

Siegelman, N., Bogaerts, L., Kronenfeld, O., & Frost, R. (2018). Redefining "learning" in statistical learning: What does an online measure reveal about the assimilation of visual regularities? *Cognitive science, 42*, 692-727.

Stevenson, R. A., Baum, S. H., Segers, M., Ferber, S., Barense, M. D., & Wallace, M. T. (2017). Multisensory speech perception in autism spectrum disorder: From phoneme to whole-word perception. *Autism Research, 10*(7), 1280-1290.

Stevenson, R. A., Ghose, D., Fister, J. K., Sarko, D. K., Altieri, N. A., Nidiffer, A. R., . . . Wallace, M. T. (2014). Identifying and Quantifying Multisensory Integration: A Tutorial Review. *Brain Topogr*. doi: 10.1007/s10548-014-0365-7

Stevenson, R. A., Segers, M., Ferber, S., Barense, M. D., Camarata, S., & Wallace, M. T. (2015). Keeping time in the brain: Autism spectrum disorder and audiovisual temporal processing. *Autism Res*. doi: 10.1002/aur.1566

Stevenson, R. A., Segers, M., Ferber, S., Barense, M. D., & Wallace, M. T. (2014). The impact of multisensory integration deficits on speech perception in children with autism spectrum disorders. *Front Psychol, 5*, 379. doi: 10.3389/fpsyg.2014.00379

Stevenson, R. A., Segers, M., Ncube, B. L., Black, K. R., Bebko, J. M., Ferber, S., & Barense, M. D. (2018). The cascading influence of multisensory processing on speech perception in autism. *Autism, 22*(5), 609-624.

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. *J Neurosci, 34*(3), 691-697. doi: 10.1523/JNEUROSCI.3615-13.2014

Stevenson, R. A., Siemann, J. K., Woynaroski, T. G., Schneider, B. C., Eberly, H. E., Camarata, S. M., & Wallace, M. T. (2014a). Brief report: arrested development of audiovisual speech perception in autism spectrum disorders. *J Autism Dev Disord, 44*(6), 1470-1477. doi: 10.1007/s10803-013-1992-7

Stevenson, R. A., Siemann, J. K., Woynaroski, T. G., Schneider, B. C., Eberly, H. E., Camarata, S. M., & Wallace, M. T. (2014b). Evidence for diminished multisensory integration in autism spectrum disorders. *J Autism Dev Disord, 44*(12), 3161-3167. doi: 10.1007/s10803-014-2179-6

Van Boxtel, J. J., & Lu, H. (2013). A predictive coding perspective on autism spectrum disorders. *Frontiers in psychology*, *4*, 19.

Wallace, M. T., & Stevenson, R. A. (2014). The construct of the multisensory temporal binding window and its dysregulation in developmental disabilities. *Neuropsychologia, 64C*, 105-123. doi: 10.1016/j.neuropsychologia.2014.08.005

Woynaroski, T. G., Kwakye, L. D., Foss-Feig, J. H., Stevenson, R. A., Stone, W. L., & Wallace, M. T. (2013). Multisensory speech perception in children with autism spectrum disorders. *J Autism Dev Disord*, *43*(12), 2891-2902. doi: 10.1007/s10803-013-1836-5

Appendix A

Ethics Approval

Date: 7 June 2018

To: Prof. Ryan Stevenson

Project ID: 109024

Study Title: Sensory Processing in development and in autism

Application Type: Continuing Ethics Review (CER) Form

Review Type: Delegated

REB Meeting Date: June 19, 2018

Date Approval Issued: 07/Jun/2018

REB Approval Expiry Date: 07/Jun/2019

Dear Prof. Ryan Stevenson,

The Western University Research Ethics Board has reviewed the application. This study, including all currently approved documents, has been re-approved until the expiry date noted above.

REB members involved in the research project do not participate in the review, discussion or decision.

Western University REB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The REB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

Sincerely,

Daniel Wyzynski, Research Ethics Coordinator, on behalf of Dr. Joseph Gilbert, HSREB Chair

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

Appendix B

Experiment I – Letter of Information

Western

<u>**Sensory Processing in development and in autism**</u>

Information letter – Adult

Prof. Ryan Stevenson

Department of Psychology

Western University

[redacted]

1. Invitation to participate

You're invited to participate in a study investigating how sensory processing influences how we interact with the world, how that changes as you grow up, and where there are differences in individuals with autism. There will be two groups of participants recruited, individuals with and without autism spectrum disorder, with 800 individuals recruited in total, ranging in age from 4 to 65.

2. Purpose of the Study

The purpose of the study is to understand how people use the things they hear and see, how they put what they hear and see together, and how this processes develops to impact how people interact with the world, particularly those with autism. Almost everything people do in the world depends on how we perceive the world. Little is known about difference in how each one of us as individuals see, hear, and feel the world around us impact our communicative abilities, social abilities, and personalities. This study seeks to explore these relationships. This project is for research only, there is no clinical therapy element involved.

3. How long will you be in the study?

The study will take from 1-4 hours, depending on which portion of the experiment you are participating in today. Behavioural, eye tracking, EEG, fMRI, and questionnaire portions will last no longer that 2 hours to complete. If you would like to complete multiple portions of the experiment, you can. Each portion will be described individually below.

4. **What are the study procedures?**

All Participants

In order to participate, individuals must: a) normal or corrected-to-normal hearing and vision; and b) no known neurological issues (epilepsy, brain injury, etc.). If you have an ASD diagnosis, we will also ask you to bring verification of diagnosis, and participant in a diagnostic verification task.

This study will take place at four possible locations on the campus of the University of Western Ontario:

1. Westminster Hall
2. Natural Sciences Centre
3. Western Interdisciplinary Research Building
4. Robarts Research Institute

Questionnaires:

You may be asked to complete several questionnaires about a range of personal skills and characteristics on paper or computer-based forms, and will be asked to complete a problem solving task and vocabulary test. This portion of participation may last up to two hours. Participation will take place at Western Universities London campus or online.

Behavioural:

You will be asked to look at pictures, listen to sounds, feel gentle taps, and watch some short videos that have been created specifically to understand how people attend to and understand what they see and what they hear. During the session, your eye movements will be recorded and tracked using eye-tracking equipment.

EEG:

If you are volunteering to participated in an EEG session, you will be asked to wear a soft, damp net over your head while you attend to the presentations that will allow us to non-invasively record your brain's activity. We will ask you to not wear makeup to an EEG session, and hair products (i.e. a hair dryer, shampoo, towels) will be provided following the EEG. This portion of participation may last up to two hours.

fMRI:

If you are volunteering to participated in an fMRI session, in order to participate, you will be screened for exclusionary criteria of the MRI itself, including:

1) Age outside of 4-65 years old
2) Weight more than 300 pounds due to scanner table limitations.
3) Significant medical illness (for example, cancer, HIV) or neurological illness (stroke, brain tumor, multiple sclerosis, epilepsy)
4) Active substance abuse or dependence in the last 3 months, excluding caffeine and nicotine
5) Head injury that has resulted in loss of consciousness for over 30 minutes
6) Pregnancy/possibility of pregnancy
7) Presence of any metal implant or shrapnel in the body
8) Claustrophobia
9) Breathing problems or motion disorders
8) Body piercing/tattoos
9) Permanent makeup
10) Dentures
11) Radiation seeds/implants
12) Pacemakers or implantable stimulation systems

Because the scanner environment is very unusual and potentially uncomfortable you will have the choice to first participate in a training program designed to familiarize you with the MRI scanning machine. In this case, participation will involve coming to Western on two occasions. On the first visit, you would practice participating in the MRI experiment in a special training facility and complete standardized tests. This includes lying on a “mock scanner” bed with a replica head coil, and being placed into an MRI scanner. You will be able to hear the noises the scanner will make, and experience what it will be like to be in the scanner. On the second visit, you will participate in the actual imaging procedure. If you are comfortable participating in the actual MRI on the first visit, that is also possible. The MRI training facility is located in room 221 of the Westminster Hall, which is located at 361 Windermere Rd. (near the corner of Windermere Rd. and Richmond St.). The actual MRI scanner is located in the Robarts Research Institute right beside the London Health Sciences Centre – University Campus on Perth Drive, just off Windermere Road in London Ontario.

Magnetic resonance imaging is a non-invasive technique that does not involve injections, x- rays, or radiation.

5. What are the risks and harms of participating?

All studies, including this study, pose the possibility of confidentiality risks. These risks will be minimized in every way possible, detailed in section 8 of this document.

fMRI only: There are no known biological risks associated with MR imaging. Some people cannot have an MRI because they have some type of metal in their body. For instance, if you have a heart pacemaker, artificial heart valves, metal implants such as metal ear implants, bullet pieces, chemotherapy or insulin pumps or any other metal such as metal clips or rings, they cannot have an MRI. During this test, you will lie in a small closed area inside a large magnetic tube. Some people may get scared or anxious in small places (claustrophobic). An MRI may also cause possible anxiety for people due to the loud banging made by the machine and the confined space of the testing area. You will be given either ear plugs or specially designed headphones to help reduce the noise.

6. What are the benefits of participating in this study?

You may not directly benefit from participating in this study but information gathered may provide benefits to society as a whole which include understanding the role that sensory perception plays in typical development, which may lead to theories and practices to help individuals who exhibit impaired sensory perception, such as those with autism.

7. Can participants choose to leave the study?

Participation is completely voluntary, *you can withdraw from the study at any time*. If you decide to stop participating, you will still be eligible to receive the promised compensation for agreeing to be in this project. In the event you withdraw from the study, all associated data collected will be immediately destroyed wherever possible.

8. How will participants' information be kept confidential?

ALL INFORMATION OBTAINED DURING THE STUDY WILL BE HELD IN STRICT CONFIDENCE TO THE FULLEST EXTENT POSSIBLE BY LAW. WHILE WE DO OUR BEST TO PROTECT YOUR INFORMATION THERE IS NO GUARANTEE THAT WE WILL BE ABLE TO DO SO. THE INCLUSION OF YOUR NAME, CONTACT INFORMATION, AND DATE OF BIRTH MAY ALLOW SOMEONE TO LINK THE DATA AND IDENTIFY YOU. TO MITIGATE THIS RISK TO THE GREATEST EXTENT POSSIBLE, ALL DATA WILL BE DE-IDENTIFIED IMMEDIATELY FOLLOWING COLLECTION AND LABELLED WITH A PARTICIPANT ID, AND THE FILE LINKING YOUR IDENTIFYING INFORMATION AND

PARTICIPANT ID WILL BE KEPT UNDER LOCK AND KEY. ONLY STUDY TEAM WILL HAVE ACCESS TO STUDY-RELATED INFORMATION, AND REPRESENTATIVES OF THE WESTERN UNIVERSITY HEALTH SCIENCES RESEARCH ETHICS BOARD MAY REQUIRE ACCESS TO YOUR STUDY-RELATED RECORDS TO MONITOR THE CONDUCT OF THE RESEARCH. THE EXPERIMENTAL DATA ACQUIRED IN THIS STUDY MAY, IN AN ANONYMIZED FORM THAT CANNOT BE CONNECTED TO YOU, BE USED FOR TEACHING PURPOSES, BE PRESENTED AT MEETINGS, PUBLISHED, SHARED WITH OTHER SCIENTIFIC RESEARCHERS OR USED IN FUTURE STUDIES. YOUR NAME OR OTHER IDENTIFYING INFORMATION WILL NOT BE USED IN ANY PUBLICATION OR TEACHING MATERIALS WITHOUT YOUR SPECIFIC PERMISSION. STUDY MATERIALS WILL BE ARCHIVED FOR 5 YEARS FOLLOWING THE COMPLETION OF THE STUDY, ANALYSIS, AND PUBLICATION.

9. **Are participants compensated to be in this study?**

Yes. Participants from the SONA system will be compensated with 1 research credit per hour toward PSYC1000 for participating in this study. If you are enrolled in a course other than Psych 1000, your compensation will be based on your course outline. If you have any questions about the time or compensation, please feel free to contact the investigators before you consider signing the consent. Otherwise, compensation will be $5.00 for every 30 minutes of participation, and if travelling from outside of London, travel expenses will be reimbursed..

10. **What are the Rights of Participants?**

Your participation in this study is voluntary. You may decide not to be in this study. Even if you consent to participate you have the right to not answer individual questions or to withdraw from the study at any time. If you choose not to participate or to leave the study at any time it will have no effect on your academic standing if you are a student.

We will give you new information that is learned during the study that might affect your decision to stay in the study.

You do not waive any legal right by signing this consent form.

11. **Whom do participants contact for questions?**

If you have questions about this research study please contact: Prof. Ryan Stevenson at the Department of Psychology, Western University, [redacted]

If you have any questions about your rights as a research participant or the conduct of this study, you may contact The Office of Research Ethics [redacted]

Thank you for your interest and participation in this study, it is greatly appreciated!

This letter is yours to keep for future reference.

Appendix C

Experiment I – Consent Form

Sensory Processing in development and in autism

INFORMED CONSENT FORM

Prof. Ryan Stevenson
Department of Psychology
Western University
[redacted]

I have read the Letter of Information, have had the nature of the study explained to me and I agree to participate. All questions have been answered to my satisfaction.

Questionnaires: ☐ Yes ☐ No

Behavioural: ☐ Yes ☐ No

EEG: ☐ Yes ☐ No

fMRI: ☐ Yes ☐ No

Name (please print): ________________________________

Signature: ________________________________

Date: ________________________________

Name of Person Obtaining Consent________________________________

Signature of Person Obtaining Consent_____________________________

Date for Person Obtaining Consent________________________________

Appendix D

Experiment II – Letter of Information

Western

Sensory Processing in development and in autism

Information letter – Adult

Prof. Ryan Stevenson

Department of Psychology

Western University

[redacted]

12. **Invitation to participate**

You're invited to participate in a study investigating how sensory processing influences how we interact with the world, how that changes as you grow up, and where there are differences in individuals with autism. There will be two groups of participants recruited, individuals with and without autism spectrum disorder, with 800 individuals recruited in total, ranging in age from 4 to 65.

13. **Purpose of the Study**

The purpose of the study is to understand how people use the things they hear and see, how they put what they hear and see together, and how this processes develops to impact how people interact with the world, particularly those with autism. Almost everything people do in the world depends on how we perceive the world. Little is known about difference in how each one of us as individuals see, hear, and feel the world around us impact our communicative abilities, social abilities, and personalities. This study seeks to explore these relationships. This project is for research only, there is no clinical therapy element involved.

14. **How long will you be in the study?**

The study will take from 1-4 hours, depending on which portion of the experiment you are participating in today. Behavioural, eye tracking, EEG, fMRI, and questionnaire portions will last no longer that 2 hours to complete. If you would like to complete multiple portions of the experiment, you can. Each portion will be described individually below.

15. **What are the study procedures?**

All Participants

In order to participate, individuals must: a) normal or corrected-to-normal hearing and vision; and b) no known neurological issues (epilepsy, brain injury, etc.). If you have an ASD diagnosis, we will also ask you to bring verification of diagnosis, and participant in a diagnostic verification task.

This study will take place at four possible locations on the campus of the University of Western Ontario:

5. Westminster Hall
6. Natural Sciences Centre
7. Western Interdisciplinary Research Building
8. Robarts Research Institute

Questionnaires:

You may be asked to complete several questionnaires about a range of personal skills and characteristics on paper or computer-based forms, and will be asked to complete a problem solving task and vocabulary test. This portion of participation may last up to two hours. Participation will take place at Western Universities London campus or online.

Behavioural:

You will be asked to look at pictures, listen to sounds, feel gentle taps, and watch some short videos that have been created specifically to understand how people attend to and understand what they see and what they hear. During the session, your eye movements will be recorded and tracked using eye-tracking equipment.

EEG:

If you are volunteering to participated in an EEG session, you will be asked to wear a soft, damp net over your head while you attend to the presentations that will allow us to non-invasively record your brain's activity. We will ask you to not wear makeup to an EEG session, and hair products (i.e. a hair dryer, shampoo, towels) will be provided following the EEG. This portion of participation may last up to two hours.

fMRI:

If you are volunteering to participated in an fMRI session, in order to participate, you will be screened for exclusionary criteria of the MRI itself, including:

1) Age outside of 4-65 years old
2) Weight more than 300 pounds due to scanner table limitations.
3) Significant medical illness (for example, cancer, HIV) or neurological illness (stroke, brain tumor, multiple sclerosis, epilepsy)
4) Active substance abuse or dependence in the last 3 months, excluding caffeine and nicotine
5) Head injury that has resulted in loss of consciousness for over 30 minutes
6) Pregnancy/possibility of pregnancy
7) Presence of any metal implant or shrapnel in the body
8) Claustrophobia
9) Breathing problems or motion disorders
8) Body piercing/tattoos
9) Permanent makeup
10) Dentures
11) Radiation seeds/implants
12) Pacemakers or implantable stimulation systems

Because the scanner environment is very unusual and potentially uncomfortable you will have the choice to first participate in a training program designed to familiarize you with the MRI scanning machine. In this case, participation will involve coming to Western on two occasions. On the first visit, you would practice participating in the MRI experiment in a special training facility and complete standardized tests. This includes lying on a “mock scanner” bed with a replica head coil, and being placed into an MRI scanner. You will be able to hear the noises the scanner will make, and experience what it will be like to be in the scanner. On the second visit, you will participate in the actual imaging procedure. If you are comfortable participating in the actual MRI on the first visit, that is also possible. The MRI training facility is located in room 221 of the Westminster Hall, which is located at 361 Windermere Rd. (near the corner of Windermere Rd. and Richmond St.). The actual MRI scanner is located in the Robarts Research Institute right beside the London Health Sciences Centre – University Campus on Perth Drive, just off Windermere Road in London Ontario.

Magnetic resonance imaging is a non-invasive technique that does not involve injections, x- rays, or radiation.

16. **What are the risks and harms of participating?**

All studies, including this study, pose the possibility of confidentiality risks. These risks will be minimized in every way possible, detailed in section 8 of this document.

fMRI only: There are no known biological risks associated with MR imaging. Some people cannot have an MRI because they have some type of metal in their body. For instance, if you have a heart pacemaker, artificial heart valves, metal implants such as metal ear implants, bullet pieces, chemotherapy or insulin pumps or any other metal such as metal clips or rings, they cannot have an MRI. During this test, you will lie in a small closed area inside a large magnetic tube. Some people may get scared or anxious in small places (claustrophobic). An MRI may also cause possible anxiety for people due to the loud banging made by the machine and the confined space of the testing area. You will be given either ear plugs or specially designed headphones to help reduce the noise.

17. **What are the benefits of participating in this study?**

You may not directly benefit from participating in this study but information gathered may provide benefits to society as a whole which include understanding the role that sensory perception plays in typical development, which may lead to theories and practices to help individuals who exhibit impaired sensory perception, such as those with autism.

18. **Can participants choose to leave the study?**

Participation is completely voluntary, *you can withdraw from the study at any time*. If you decide to stop participating, you will still be eligible to receive the promised compensation for agreeing to be in this project. In the event you withdraw from the study, all associated data collected will be immediately destroyed wherever possible.

19. **How will participants' information be kept confidential?**

ALL INFORMATION OBTAINED DURING THE STUDY WILL BE HELD IN STRICT CONFIDENCE TO THE FULLEST EXTENT POSSIBLE BY LAW. WHILE WE DO OUR BEST TO PROTECT YOUR INFORMATION THERE IS NO GUARANTEE THAT WE WILL BE ABLE TO DO SO. THE INCLUSION OF YOUR NAME, CONTACT INFORMATION, AND DATE OF BIRTH MAY ALLOW SOMEONE TO LINK THE DATA AND IDENTIFY YOU. TO MITIGATE THIS RISK TO THE GREATEST EXTENT POSSIBLE, ALL DATA WILL BE DE-IDENTIFIED IMMEDIATELY FOLLOWING COLLECTION AND LABELLED WITH A PARTICIPANT ID, AND THE FILE LINKING YOUR IDENTIFYING INFORMATION AND

Participant ID will be kept under lock and key. Only study team will have access to study-related information, and representatives of the Western University Health Sciences Research Ethics Board may require access to your study-related records to monitor the conduct of the research. The experimental data acquired in this study may, in an anonymized form that cannot be connected to you, be used for teaching purposes, be presented at meetings, published, shared with other scientific researchers or used in future studies. Your name or other identifying information will not be used in any publication or teaching materials without your specific permission. Study materials will be archived for 5 years following the completion of the study, analysis, and publication.

20. **Are participants compensated to be in this study?**

Yes. Participants from the SONA system will be compensated with 1 research credit per hour toward PSYC1000 for participating in this study. If you are enrolled in a course other than Psych 1000, your compensation will be based on your course outline. If you have any questions about the time or compensation, please feel free to contact the investigators before you consider signing the consent. Otherwise, compensation will be $5.00 for every 30 minutes of participation, and if travelling from outside of London, travel expenses will be reimbursed..

21. **What are the Rights of Participants?**

Your participation in this study is voluntary. You may decide not to be in this study. Even if you consent to participate you have the right to not answer individual questions or to withdraw from the study at any time. If you choose not to participate or to leave the study at any time it will have no effect on your academic standing if you are a student.

We will give you new information that is learned during the study that might affect your decision to stay in the study.

You do not waive any legal right by signing this consent form.

22. **Whom do participants contact for questions?**

If you have questions about this research study please contact: Prof. Ryan Stevenson at the Department of Psychology, Western University, [redacted]

If you have any questions about your rights as a research participant or the conduct of this study, you may contact The Office of Research Ethics [redacted].

Thank you for your interest and participation in this study, it is greatly appreciated!

This letter is yours to keep for future reference.

Appendix E

Experiment II – Consent Form

Sensory Processing in development and in autism

INFORMED CONSENT FORM

Prof. Ryan Stevenson
Department of Psychology
Western University
[redacted]

I have read the Letter of Information, have had the nature of the study explained to me and I agree to participate. All questions have been answered to my satisfaction.

Questionnaires: ☐ Yes ☐ No

Behavioural: ☐ Yes ☐ No

EEG: ☐ Yes ☐ No

fMRI: ☐ Yes ☐ No

Name (please print): ________________________________

Signature: ________________________________

Date: ________________________________

Name of Person Obtaining Consent________________________________

Signature of Person Obtaining Consent_____________________________

Date for Person Obtaining Consent________________________________

Appendix F

Experiment I – Questionnaires

AQ

The Adult AQ

Participant # _______ **Sex** ____________________ **Handedness** __________________

Age _______________ **Date of birth** _____________ **Today's Date** __________________

Instructions: *Below are a list of statements. Please read each statement* *very carefully* *and rate how strongly you agree or disagree with it by circling your answer.*

DO NOT SKIP ANY STATEMENT.

Examples

E1. I am willing to take risks.	definitely agree	slightly agree	slightly disagree	definitely disagree
E2. I like playing board games.	definitely agree	slightly agree	slightly disagree	definitely disagree
E3. I find learning to play musical instruments easy.	definitely agree	slightly agree	slightly disagree	definitely disagree
E4. I am fascinated by other cultures.	definitely agree	slightly agree	slightly disagree	definitely disagree

---

1. I prefer to do things with others rather than on my own.	definitely agree	slightly agree	slightly disagree	definitely disagree
2. I prefer to do things the same way over and over again.	definitely agree	slightly agree	slightly disagree	definitely disagree
3. If I try to imagine something, I find it very easy to create a picture in my mind.	definitely agree	slightly agree	slightly disagree	definitely disagree
4. I frequently get so strongly absorbed in one thing that I lose sight of other things.	definitely agree	slightly agree	slightly disagree	definitely disagree
5. I often notice small sounds when others do not.	definitely agree	slightly agree	slightly disagree	definitely disagree
6. I usually notice car number plates or similar strings of information.	definitely agree	slightly agree	slightly disagree	definitely disagree
7. Other people frequently tell me that what I've said is impolite, even though I think it is polite.	definitely agree	slightly agree	slightly disagree	definitely disagree
8. When I'm reading a story, I can easily imagine what the characters might	definitely agree	slightly agree	slightly disagree	definitely disagree

look like.				
9. I am fascinated by dates.	definitely agree	slightly agree	slightly disagree	definitely disagree
10. In a social group, I can easily keep track of several different people's conversations.	definitely agree	slightly agree	slightly disagree	definitely disagree
11. I find social situations easy.	definitely agree	slightly agree	slightly disagree	definitely disagree
12. I tend to notice details that others do not.	definitely agree	slightly agree	slightly disagree	definitely disagree
13. I would rather go to a library than a party.	definitely agree	slightly agree	slightly disagree	definitely disagree
14. I find making up stories easy.	definitely agree	slightly agree	slightly disagree	definitely disagree
15. I find myself drawn more strongly to people than to things.	definitely agree	slightly agree	slightly disagree	definitely disagree
16. I tend to have very strong interests which I get upset about if I can't pursue.	definitely agree	slightly agree	slightly disagree	definitely disagree
17. I enjoy social chit-chat.	definitely agree	slightly agree	slightly disagree	definitely disagree
18. When I talk, it isn't always easy for others to get a word in edgeways.	definitely agree	slightly agree	slightly disagree	definitely disagree
19. I am fascinated by numbers.	definitely agree	slightly agree	slightly disagree	definitely disagree
20. When I'm reading a story, I find it difficult to work out the characters' intentions.	definitely agree	slightly agree	slightly disagree	definitely disagree
21. I don't particularly enjoy reading fiction.	definitely agree	slightly agree	slightly disagree	definitely disagree
22. I find it hard to make new friends.	definitely agree	slightly agree	slightly disagree	definitely disagree
23. I notice patterns in things all the time.	definitely agree	slightly agree	slightly disagree	definitely disagree
24. I would rather go to the theatre than a museum.	definitely agree	slightly agree	slightly disagree	definitely disagree
25. It does not upset me if my daily routine is disturbed.	definitely agree	slightly agree	slightly disagree	definitely disagree
26. I frequently find that I don't know how to keep a conversation going.	definitely agree	slightly agree	slightly disagree	definitely disagree
27. I find it easy to "read between the lines" when someone is talking to me.	definitely agree	slightly agree	slightly disagree	definitely disagree
28. I usually concentrate more on the whole picture, rather than the small details.	definitely agree	slightly agree	slightly disagree	definitely disagree
29. I am not very good at remembering phone numbers.	definitely agree	slightly agree	slightly disagree	definitely disagree

30. I don't usually notice small changes in a situation, or a person's appearance.	definitely agree	slightly agree	slightly disagree	definitely disagree
31. I know how to tell if someone listening to me is getting bored.	definitely agree	slightly agree	slightly disagree	definitely disagree
32. I find it easy to do more than one thing at once.	definitely agree	slightly agree	slightly disagree	definitely disagree
33. When I talk on the phone, I'm not sure when it's my turn to speak.	definitely agree	slightly agree	slightly disagree	definitely disagree
34. I enjoy doing things spontaneously.	definitely agree	slightly agree	slightly disagree	definitely disagree
35. I am often the last to understand the point of a joke.	definitely agree	slightly agree	slightly disagree	definitely disagree
36. I find it easy to work out what someone is thinking or feeling just by looking at their face.	definitely agree	slightly agree	slightly disagree	definitely disagree
37. If there is an interruption, I can switch back to what I was doing very quickly.	definitely agree	slightly agree	slightly disagree	definitely disagree
38. I am good at social chit-chat.	definitely agree	slightly agree	slightly disagree	definitely disagree
39. People often tell me that I keep going on and on about the same thing.	definitely agree	slightly agree	slightly disagree	definitely disagree
40. When I was young, I used to enjoy playing games involving pretending with other children.	definitely agree	slightly agree	slightly disagree	definitely disagree
41. I like to collect information about categories of things (e.g. types of car, types of bird, types of train, types of plant, etc.).	definitely agree	slightly agree	slightly disagree	definitely disagree
42. I find it difficult to imagine what it would be like to be someone else.	definitely agree	slightly agree	slightly disagree	definitely disagree
43. I like to plan any activities I participate in carefully.	definitely agree	slightly agree	slightly disagree	definitely disagree
44. I enjoy social occasions.	definitely agree	slightly agree	slightly disagree	definitely disagree
45. I find it difficult to work out people's intentions.	definitely agree	slightly agree	slightly disagree	definitely disagree
46. New situations make me anxious.	definitely agree	slightly agree	slightly disagree	definitely disagree
47. I enjoy meeting new people.	definitely agree	slightly agree	slightly disagree	definitely disagree
48. I am a good diplomat.	definitely agree	slightly agree	slightly disagree	definitely disagree
49. I am not very good at remembering people's date of birth.	definitely agree	slightly agree	slightly disagree	definitely disagree
50. I find it very easy to play games with children that involve pretending.	definitely agree	slightly agree	slightly disagree	definitely disagree

BAPQ

BAPQ

Participant # _______ **Sex** ____________________ **Handedness** __________________

Age ______________ **Date of birth** ____________ **Today's Date** __________________

Instructions: You are about to fill out a series of statements related to personality and lifestyle. For each question, circle that answer that best describes how often that statement applies to you. *Many of these questions ask about your interactions with other people. Please think about the way you are with most people, rather than special relationships you may have with spouses or significant others, children, siblings, and parents.* Everyone changes over time, which can make it hard to fill out questions about personality. Think about the way you have been the majority of your adult life, rather than the way you were as a teenager, or times you may have felt different than normal. You must answer each question, and give only one answer per question. If you are confused, please give it your best guess.

1. I like being around other people	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
2. I find it hard to get my words out smoothly	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
3. I am comfortable with unexpected changes in plans	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
4. It's hard for me to avoid getting sidetracked in conversation	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
5. I would rather talk to people to get information than to socialize	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
6. People have to talk me into trying something new	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
7. I am "in-tune" with the other person during conversation	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
8. I have to warm myself up to the idea of visiting an unfamiliar place	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
9. I enjoy being in social situations	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
10. My voice has a flat or monotone sound to it	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
11. I feel disconnected or "out of sync" in conversations with others	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
12. People find it easy to approach me	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
13. I feel a strong need for sameness from day to day	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often

14. People ask me to repeat things I've said because they don't understand	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
15. I am flexible about how things should be done	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
16. I look forward to situations where I can meet new people	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
17. I have been told that I talk too much about certain topics	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
18. When I make conversation it is just to be polite	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
19. I look forward to trying new things	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
20. I speak too loudly or softly	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
21. I can tell when someone is not interested in what I am saying	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
22. I have a hard time dealing with changes in my routine	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
23. I am good at making small talk	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
24. I act very set in my ways	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
25. I feel like I am really connecting with other people	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
26. People get frustrated by my unwillingness to bend	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
27. Conversation bores me	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
28. I am warm and friendly in my interactions with others	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
29. I leave long pauses in conversation	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
30. I alter my daily routine by trying something different	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
31. I prefer to be alone rather than with others	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
32. I lose track of my original point when talking to people	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
33. I like to closely follow a routine while working	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
34. I can tell when it is time to change topics in conversation	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
35. I keep doing things the way I know, even if another way might be better	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often
36. I enjoy chatting with people	Very Rarely	Rarely	Occasionally	Somewhat Often	Often	Very Often

MSCS

MSCS- Self Report Jodi Yager, PhD and Grace Iarocci, PhD

Your Name (First, Middle, Last): ______________________________

Today's Date (Month, Day, Year): ____________________

Instructions: For each item, circle the number that best describes your behaviour over the **past six months**.

1 = Not True or Almost Never True
2 = Rarely True
3 = Sometimes True
4 = Often True
5 = Very True or Almost Always True

Many of the items may seem similar to one another, but your response on each one is very important. If you are unsure of an item, please put your best estimate.

1 = NOT TRUE OR ALMOST NEVER TRUE	2 = RARELY TRUE	3 = SOMETIMES TRUE	4 = OFTEN TRUE	5 = VERY TRUE OR ALMOST ALWAYS TRUE

1. I prefer to spend time alone (e.g., I am most content when left on my own).	1 2 3 4 5
2. I enjoy meeting new people.	1 2 3 4 5
3. I easily recognize unfriendly actions. For example, I know when someone is making fun of me in a mean-spirited way. Or, I recognize when a peer is pressuring me to do something I shouldn't or don't want to do.	1 2 3 4 5
4. I disagree with people without fighting or arguing.	1 2 3 4 5
5. I apologize after hurting someone (without being prompted or told to).	1 2 3 4 5
6. I talk "over" people in conversations (e.g., interrupt a lot, don't wait for others to finish speaking).	1 2 3 4 5
7. I shift conversations to my favourite topic or interest.	1 2 3 4 5
8. I talk about the same things over and over ("get stuck" on certain topics).	1 2 3 4 5
9. I am sensitive to the feelings and concerns of others.	1 2 3 4 5
10. I initiate friendly social "chit-chat" with people (e.g., ask about what's new with other person, talk about the weather or events). These are casual conversations that often have no specific purpose.	1 2 3 4 5
11. I appear visibly upset when I see people suffering (in real life or on tv/film).	1 2 3 4 5
12. I have trouble joining conversations appropriately (e.g., I may interrupt or "butt in" without waiting for a good time to join in; or, I may start talking about a topic of interest to me regardless of the ongoing conversation).	1 2 3 4 5
13. I misread social cues.	1 2 3 4 5
14. I stay in the "background" in group social situations (e.g., keep to myself, may not be noticed).	1 2 3 4 5

1 = NOT TRUE OR ALMOST NEVER TRUE	2 = RARELY TRUE	3 = SOMETIMES TRUE	4 = OFTEN TRUE	5 = VERY TRUE OR ALMOST ALWAYS TRUE

15. I am patient (e.g., when waiting).	1 2 3 4 5
16. I express concern for others when they are upset or distressed (e.g., may ask "are you alright?" or ask if they need anything).	1 2 3 4 5
17. I look people in the eye when talking to them.	1 2 3 4 5
18. I get frustrated easily.	1 2 3 4 5
19. I ask people questions about themselves or their lives (e.g., how they are, what they've been up to).	1 2 3 4 5
20. I do not offer to help people (unless asked or told to).	1 2 3 4 5
21. My emotional responses tend to be extreme (e.g., I might be extremely angry or frustrated in response to relatively small problems).	1 2 3 4 5
22. I avoid talking to people when possible (e.g., look, move, or walk away).	1 2 3 4 5
23. My facial expressions are easy to read.	1 2 3 4 5
24. I can tell when people are joking.	1 2 3 4 5
25. I stay calm when problems come up.	1 2 3 4 5
26. I know about the latest trends for my age (e.g., in clothes, music, tv shows/movies, music).	1 2 3 4 5
27. I am indifferent or "oblivious" to people who are upset (or in distress).	1 2 3 4 5
28. I pick up on subtle hints and indirect requests. For example, I would understand that when someone asks "Can you reach that book?", they are asking me to pass it to them. In other words, I can "read between the lines" when others are talking.	1 2 3 4 5
29. My smiles seem forced or awkward.	1 2 3 4 5
30. I give compliments to people.	1 2 3 4 5
31. I act appropriately for my age in public (e.g., restaurants, movie theatres, libraries, doctor's waiting rooms, etc).	1 2 3 4 5

32. I use eye contact to get other people's attention (e.g., to start a conversation, ask a question).	1 2 3 4 5
33. I change the volume of my voice depending on where I am (e.g., quiet at the library or movies but louder when outside or at a sporting event).	1 2 3 4 5
34. I show a range of facial expressions (e.g., embarrassed, guilty, surprised, disgusted, pleased).	1 2 3 4 5
35. I smile appropriately in social situations (e.g., if given a compliment, greeting someone, in response to someone smiling at me).	1 2 3 4 5
36. I act out when angry or upset (e.g., yell at, hit, or shove people).	1 2 3 4 5
37. I talk "at" people (e.g., almost like I am giving a lecture).	1 2 3 4 5
38. I go off track during conversations (e.g., I might change topics suddenly as if thinking aloud or reminded of something else; or, I might gradually get sidetracked or lose track of my original point).	1 2 3 4 5
39. I am concerned about people and their problems (e.g., talk to someone who is having a hard time).	1 2 3 4 5
40. I am naïve (believe whatever I am told).	1 2 3 4 5
41. I get over setbacks or disappointments quickly.	1 2 3 4 5
42. I need to be told or prompted to talk or interact with people.	1 2 3 4 5

1 = NOT TRUE OR ALMOST NEVER TRUE	2 = RARELY TRUE	3 = SOMETIMES TRUE	4 = OFTEN TRUE	5 = VERY TRUE OR ALMOST ALWAYS TRUE

43. I follow social "rules" around privacy (e.g., respect people's privacy when they are changing/ in the washroom; knock on closed doors instead of barging in).	1 2 3 4 5
44. I get very anxious.	1 2 3 4 5
45. I can see things from another person's perspective.	1 2 3 4 5
46. I have "meltdowns" (e.g., sudden outbursts, "blow ups" temper tantrums).	1 2 3 4 5
47. My expectations of friends are reasonable. For example, I know that they have other friends or are not always available.	1 2 3 4 5
48. I offer comfort to people (e.g., to someone who is upset, not feeling well, hurt etc.). For instance, I may try to hug the person or provide a comforting object as a way of trying to make the other person feel better.	1 2 3 4 5
49. I use appropriate gestures when communicating with people (e.g., nodding/shaking head, waving goodbye, pointing at something interesting or far away, giving thumbs up, putting finger to lips for "be quiet", etc.).	1 2 3 4 5
50. I am good at taking turns in conversations (e.g., my conversations have age -appropriate levels of back-and-forth with each person getting a chance to talk; I respond appropriately to the other person's questions or statements).	1 2 3 4 5
51. My facial expressions seem "flat" (e.g., my face may be like a "blank slate" or seem overly serious).	1 2 3 4 5
52. I have trouble judging who is trustworthy (e.g., who to share secrets or personal information with).	1 2 3 4 5
53. I understand what makes a true friend.	1 2 3 4 5
54. I recognize when people are trying to take advantage of me.	1 2 3 4 5
55. I try to cheer people up (when they are down).	1 2 3 4 5
56. I give other people a chance to speak during conversations (e.g., pauses, asks them questions).	1 2 3 4 5

57. I seek out people to spend time with (e.g., friends, other people).	1 2 3 4 5
58. I understand the "social hierarchy" at school or work or in other settings (e.g., understand that teachers or supervisors are in a position of authority).	1 2 3 4 5
59. I have trouble predicting what other people will do or how they will react.	1 2 3 4 5
60. I get very upset if things are not done my way.	1 2 3 4 5
61. I dominate conversations so that it can be hard for others to "get a word in". For example, I might ramble on and on about a favourite topic of interest. I might also need reminders/prompting to let others speak.	1 2 3 4 5
62. I sound the same (have the same tone and intonation in my voice) regardless of how I am feeling. In other words, it is hard to tell what I am feeling based on the way my voice sounds.	1 2 3 4 5
63. I provide too much detail when talking about a topic (e.g., I might list a bunch of facts rather than expressing a main message or exchanging information).	1 2 3 4 5
64. I congratulate people when good things happen to them.	1 2 3 4 5
65. I initiate get-togethers with peers (e.g., call or email or text them to make plans).	1 2 3 4 5
66. I point at things when appropriate (e.g., to get another person to look at something far away).	1 2 3 4 5
67. I do not pick up on the subtleties of social interaction.	1 2 3 4 5

1 = NOT TRUE OR ALMOST NEVER TRUE	2 = RARELY ; TRUE	3 = SOMETIMES TRUE	4 = OFTEN TRUE	5 = VERY TRUE OR ALMOST ALWAYS TRUE

68. My emotions tend to be "all or nothing" ("all on" or "all off").	1 2 3 4 5
69. I show little interest in people.	1 2 3 4 5
70. I speak with a flat, monotonous tone of voice.	1 2 3 4 5
71. I understand that it is important to have good personal hygiene (e.g., smelling and looking clean).	1 2 3 4 5
72. I change my behaviour to suit the situation. For example, I might be more polite/ formal around authority figures like teachers or supervisors but be more casual around peers. As another example, I might change my way of speaking depending on who I am talking to (e.g., talk more simply to a younger child).	1 2 3 4 5
73. I dress appropriately for my age and social situation (e.g., dress up for formal events, wear more casual clothes on weekends, wear clothes that are generally considered acceptable by peers my age).	1 2 3 4 5
74. I talk too much.	1 2 3 4 5
75. I hide my true feelings (when necessary) so that I don't come across as rude (e.g., I might hide feelings of disappointment when given a gift that I do not like or when someone breaks something of mine by accident).	1 2 3 4 5
76. I introduce myself to people (without being told to).	1 2 3 4 5
77. I understand when people are being sarcastic.	1 2 3 4 5

Self Report Feedback:

1. Were any items difficult to answer (provide item number) and explain why

____

____

____

____

2. Any comments or suggestions:

____

____

____

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Appendix G

Experiment II – Questionnaires

ASRS

Adult ADHD Self-Report Scale (ASRS-v1.1) Symptom Checklist Instructions

The questions on the back page are designed to stimulate dialogue between you and your patients and to help confirm if they may be suffering from the symptoms of attention-deficit/hyperactivity disorder (ADHD).

Description: The Symptom Checklist is an instrument consisting of the eighteen DSM-IV-TR criteria. Six of the eighteen questions were found to be the most predictive of symptoms consistent with ADHD. These six questions are the basis for the ASRS v1.1 Screener and are also Part A of the Symptom Checklist. Part B of the Symptom Checklist contains the remaining twelve questions.

Instructions:

Symptoms

1. Ask the patient to complete both Part A and Part B of the Symptom Checklist by marking an X in the box that most closely represents the frequency of occurrence of each of the symptoms.

2. Score Part A. If four or more marks appear in the darkly shaded boxes within Part A then the patient has symptoms highly consistent with ADHD in adults and further investigation is warranted.

3. The frequency scores on Part B provide additional cues and can serve as further probes into the patient's symptoms. Pay particular attention to marks appearing in the dark shaded boxes. The frequency-based response is more sensitive with certain questions. No total score or diagnostic likelihood is utilized for the twelve questions. It has been found that the six questions in Part A are the most predictive of the disorder and are best for use as a screening instrument.

Impairments

1. Review the entire Symptom Checklist with your patients and evaluate the level of impairment associated with the symptom.

2. Consider work/school, social and family settings.

3. Symptom frequency is often associated with symptom severity, therefore the Symptom Checklist may also aid in the assessment of impairments. If your patients have frequent symptoms, you may want to ask them to describe how these problems have affected the ability to work, take care of things at home, or get along with other people such as their spouse/significant other.

History

1. Assess the presence of these symptoms or similar symptoms in childhood. Adults who have ADHD need not have been formally diagnosed in childhood. In evaluating a patient's history, look for evidence of early-appearing and long-standing problems with attention or self-control. Some significant symptoms should have been present in childhood, but full symptomology is not necessary.

Version: 16/03/2017

Adult ADHD Self-Report Scale (ASRS-v1.1) Symptom Checklist

Patient Name		Today's Date	

Please answer the questions below, rating yourself on each of the criteria shown using the scale on the right side of the page. As you answer each question, place an X in the box that best describes how you have felt and conducted yourself over the past 6 months. Please give this completed checklist to your healthcare professional to discuss during today's appointment.	Never	Rarely	Sometimes	Often	Very Often
1. How often do you have trouble wrapping up the final details of a project, once the challenging parts have been done?					
2. How often do you have difficulty getting things in order when you have to do a task that requires organization?					
3. How often do you have problems remembering appointments or obligations?					
4. When you have a task that requires a lot of thought, how often do you avoid or delay getting started?					
5. How often do you fidget or squirm with your hands or feet when you have to sit down for a long time?					
6. How often do you feel overly active and compelled to do things, like you were driven by a motor?					

Part A

	Never	Rarely	Sometimes	Often	Very Often
7. How often do you make careless mistakes when you have to work on a boring or difficult project?					
8. How often do you have difficulty keeping your attention when you are doing boring or repetitive work?					
9. How often do you have difficulty concentrating on what people say to you, even when they are speaking to you directly?					
10. How often do you misplace or have difficulty finding things at home or at work?					
11. How often are you distracted by activity or noise around you?					
12. How often do you leave your seat in meetings or other situations in which you are expected to remain seated?					
13. How often do you feel restless or fidgety?					
14. How often do you have difficulty unwinding and relaxing when you have time to yourself?					
15. How often do you find yourself talking too much when you are in social situations?					
16. When you're in a conversation, how often do you find yourself finishing the sentences of the people you are talking to, before they can finish them themselves?					
17. How often do you have difficulty waiting your turn in situations when turn taking is required?					
18. How often do you interrupt others when they are busy?					

Part B

Version: 16/03/2017

The Value of Screening for Adults With ADHD

Research suggests that the symptoms of ADHD can persist into adulthood, having a significant impact on the relationships, careers, and even the personal safety of your patients who may suffer from it.[1-4] Because this disorder is often misunderstood, many people who have it do not receive appropriate treatment and, as a result, may never reach their full potential. Part of the problem is that it can be difficult to diagnose, particularly in adults.

The Adult ADHD Self-Report Scale (ASRS-v1.1) Symptom Checklist was developed in conjunction with the World Health Organization (WHO), and the Workgroup on Adult ADHD that included the following team of psychiatrists and researchers:

- **Lenard Adler, MD**
  Associate Professor of Psychiatry and Neurology
  New York University Medical School
- **Ronald C. Kessler, PhD**
  Professor, Department of Health Care Policy
  Harvard Medical School
- **Thomas Spencer, MD**
  Associate Professor of Psychiatry
  Harvard Medical School

As a healthcare professional, you can use the ASRS v1.1 as a tool to help screen for ADHD in adult patients. Insights gained through this screening may suggest the need for a more in-depth clinician interview. The questions in the ASRS v1.1 are consistent with DSM-IV criteria and address the manifestations of ADHD symptoms in adults. Content of the questionnaire also reflects the importance that DSM-IV places on symptoms, impairments, and history for a correct diagnosis.[4]

The checklist takes about 5 minutes to complete and can provide information that is critical to supplement the diagnostic process.

References:
1. Schweitzer JB, et al. Med Clin North Am. 2001;85(3):10-11, 757-777.
2. Barkley RA. Attention Deficit Hyperactivity Disorder: A Handbook for Diagnosis and Treatment. 2nd ed. 1998.
3. Biederman J, et al. Am J Psychiatry.1993;150:1792-1798.
4. American Psychiatric Association: Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition, Text Revision. Washington, DC, American Psychiatric Association. 2000: 85-93.

Appendix H

Supplementary Material for Chapter 3

Auditory statistical learning paradigm

The language exposure phase consisted of 360 tokens of each word in random order, with no word presented twice in sequence. The language maintained a consistent speech rate (average 5.1 syllables/s) and was normalized to a pitch of F0 = 196 Hz. For each of the 36 test items, participants heard a trained word from the artificial language paired with a nonword foil, separated by 500ms of silence. Nonword foils were constructed from the same syllable inventory as the words from the artificial language, where transitional probabilities between syllables were 0.0: *pubati, tapudi, dupitu, tipabu, bidata, batipi*. For the test phase, instructions were displayed on the computer screen, asking participants *'which of these two words sounds most like something you heard in the language'* where they then indicated their response on a keyboard by pressing the "*A*" or "*L*" key for the first or second "word", respectively. Overall accuracy on the 2AFC test phase were analyzed.

Visual statistical learning paradigm

During the learning phase, participants passively viewed the stream of shapes for 10 minutes, with each triplet sequence appearing 24 times. Shapes were presented for 800ms, with a 200ms inter-stimulus interval (ISI). The test phase began immediately and consisted of 42 test items of varying difficultly. The first block of 34 four trials were pattern recognition items. Pattern recognition items included both pairs of shapes (part triplets) and triplets. Participants were instructed to *'choose the pattern that appeared together in the first part'* for 24 triplet items, sixteen being 2AFC and eight 4AFC and *'choose the pattern that you are most familiar with as a whole'* for ten part-triplet items, six being 2AFC and four 4AFC. All responses were numbered, and participants indicated their response by clicking the corresponding key on a keyboard. The next eight trials were pattern completion items. For these trials, participants were shown an incomplete trained sequence, and selected the shape that best completed the sequence from a set of three possible responses. Participants were instructed to *'choose the shape that best completes the pattern'* from the 3AFC items, which included four triplet-completion items and four pair-completion (part-triplet) items. For all test trials, there was only one triplet or part-triplet that followed the statistical regularities presented in the test phase. Accuracy scores were analyzed.

Curriculum Vitae

CURRICULUM VITAE
Kaitlyn Parks
Department of Psychology
The University of Western Ontario

Education

2017-present Master's of Science: Psychology (Cognitive, Developmental, and Brain Sciences).
University of Western Ontario
Thesis title: The Impact of Statistical Learning on Language and Social Competency in ASD and ADHD: Divergent Findings
Advisor: Dr. Ryan Stevenson, Ph.D.

2011-2016 Bachelor of Science (Honours): Psychology.
Trent University
Thesis title: Language, Working Memory, and Figurative Language in Children with and without Language Problems.
Advisor: Dr. Nancie Im-Bolter, Ph.D., C. Psych.

Research Experience

2017-present Research Assistant, supervised by Dr. Ryan Stevenson, University of Western Ontario.

2016-2017 Research Assistant, supervised by Dr. Nancie Im-Bolter, Trent University.

2015-2016 Research Assistant, supervised by Dr. Alexandra Hernandez Ontario Shores Hospital.

2015-2016 Advanced Research Practicum, supervised by Dr. Nancie Im-Bolter, Trent University.

Scholarships and Awards

2019-2022 Social Sciences and Humanities Research Council of Canada (SSHRC), University of Western Ontario, total value $105,000

2019-2020 Ontario Graduate Scholarship, University of Western Ontario, total value $15,000 – declined

2019-2020 Ralph S. Devereux Award, University of Western Ontario, total value $1,800

2019 Clinical and Mental Health Poster Award, Child Health Research Day, London Health Sciences Centre, London, Ontario

2018-2019 Autism Scholars Award, total value $18,000

2018 -2019 Ontario Graduate Scholarship, University of Western Ontario, total value $15,000

2018-2019 C. Kingsley Allison Research Grant Winner, Developmental Disabilities Program, University of Western Ontario, total value $8,500

2016-2017 Gordon Winocur Research Excellence Prize, Developmental Psychology Recognition Winner – Trent University, total value $325

2015-2016 In-Course Scholarship – Trent University, total value $1,000

2015-2016 Dean's List Honour Roll Recipient, Trent University

Publications

4. **Parks, K.,** Stevenson, R. (2018). Auditory and visual statistical learning are not related to ADHD symptomatology: Evidence from a research domain criteria (RDoC) approach. *Frontiers in Psychology, 9*, 2502.

3. **Parks, K.,** Griffith, L., Noonan, N., Stevenson, R. (under review.) Statistical learning and social communication: The mediating role of language. *Scientific Reports.*

2. **Parks, K.,** Oram-Cardy, J., Woynaroski, T., Stevenson, R. (under review.) Investigating the Role of Inattention and Hyperactivity-Impulsivity in Language and Social Functioning in ADHD Using a Dimensional Approach. *Journal of Communication Disorders.*

1. **Parks, K.,** Stevenson, R. (in prep.) Sensory Processing in ASD and ADHD: A Confirmatory Factor Analysis. Manuscript in preparation.

Invited Talks

1. Statistical Learning Through Multiple Methods: Implications for Language and Social Functioning in Autism (May 2019). Vanderbilt University. Nashville, Tennessee.

Oral Presentations

5. **Parks, K.**, Schulz, S., Stevenson, R. (May 2019). Sensory Processing in ASD and ADHD: A Multi-Groups Approach. Presented at Developmental Disabilities Academic Research Day. Western University, ON.

4. **Parks, K.** (May 2018). Statistical Learning and Social Communication: The Mediating Role of Language. Presented at 31st Annual Paediatric Research Day. Western University, ON.

3. **Parks, K.** (May 2018). Statistical Learning and Social Communication: The Mediating Role of Language. Presented at Developmental Disabilities Academic Research Day. Western University, ON.

2. **Parks, K.** (April 2017). Cryonics: The Possibility of Life After Death. Paper presented at Trent University Annual Philosophy Symposium. Peterborough, ON.

1. **Parks, K.** (March 2017). Language, Working Memory, and Figurative Language in Children with and without Language Problems. Trent University Annual 3 Minute Paper Competition. Peterborough, ON.

Conference Presentations

11. **Parks, K.,** Schulz, S.E, Anagnostou, E., Nicolson, R., Kelley, E., Georgiades, S., Crosbie, J., Schachar, R., Liu, X., Segers, M., Stevenson, R. (May 2019). Sensory Processing in ASD and ADHD: A Multi-Groups Approach. Child Health Research Day. London, ON.

10. **Parks, K.,** Schulz, S.E, Segers, M., Anagnostou, E., Nicolson, R., Kelley, E., Georgiades, S., Crosbie, J., Schachar, R., Liu, X., Stevenson, R. (May 2019). Using Sensory Processing Behaviors to Differentiate ASD and ADHD Diagnoses. The 2019 International Society for Autism Research. Montreal, Quebec.

9. Schulz, S. E., **Parks, K.,** Anagnostou, E., Nicolson, R., Kelley, E., Georgiades, S., Crosbie, J., Schachar, R., Liu, X., Stevenson, R. (May 2019). Sensory processing as a transdiagnostic mechanism for behavioural outcomes in ASD and ADHD. The 2019 International Society for Autism Research. Montreal, Quebec.

8. **Parks, K.,** Schulz, S.E, Anagnostou, E., Nicolson, R., Kelley, E., Georgiades, S., Crosbie, J., Schachar, R., Liu, X., Segers, M., Stevenson, R. (May 2019). Sensory Processing in ASD and ADHD: A Multi-Groups Approach. The 2019 International Society for Autism Research. Montreal, Quebec.

7. Sehl, C., **Parks, K.,** Tran, B., Dalal, T., Schulz, S.E, Stevenson, R. (Feb 2019). A Temporal Community Structure Approach to Statistical Learning. The 48th Annual Lake Ontario Visionary Establishment (LOVE) Conference. Niagara Falls, ON.

6. Brierley, N., McDonnell, C., Schulz, S.E, **Parks, K.,** Shafai, F., Muller, A.M., Stevenson, R. (Feb 2019). Factor structure of repetitive behaviors in children with ASD and ADHD. The 48th Annual Lake Ontario Visionary Establishment (LOVE) Conference. Niagara Falls, ON.

5. Hawkins, A., Schulz, S.E, Stow, M., Shafai, F., Brierley, N., Altoum, E., Gateman, L., Garabedian, M., Abraham, A., Tse Wing, W., **Parks, K.,** Stevenson, R. (Feb 2019). Hypersensitivity and Autistic Traits in Undergraduate Students. The 48th Annual Lake Ontario Visionary Establishment (LOVE) Conference. Niagara Falls, ON.

4. **Parks, K.,** Griffith, L., Noonan, B. N., Stevenson, R. (May 2018). Statistical Learning and Autism-related Social Communication Difficulties. The 2018 International Society for Autism Research. Rotterdam, Netherlands.

3. **Parks, K.,** Griffith, L., Stevenson, R. (February 2018). The Impact of Statistical Learning on Autism-related Language and Social Communication Difficulties. The 47th Annual Lake Ontario Visionary Establishment (LOVE) Conference. Niagara Falls, ON.

2. Bailey, K., **Parks, K.,** Im-Bolter, N. (April 2017). Let's Talk About It: Language and Social Cognition in Children With Epilepsy. The 27th Annual Meeting of the Canadian Society for Brain, Behaviour, and Cognitive Sciences. Regina, SK.

1. O'Neil-Watts, S., Doddrell, P., Hernandez, A., Wilson, K., **Parks, K.,** Astell, A (March 2016). Evaluating pre-existing touch screen applications for people with dementia (InTouch). Ontario Shores' 5th Annual Mental Health Conference. Whitby, ON.

Undergraduate Trainees

2018 – 2019 Claudia Sehl - Thesis: *A Temporal Community Structure Approach to Statistical Learning.*
Ben Tran
Ammar Haque
Tyler Dalal
Elizabeth Gateman

2017 – 2018 Laura Griffith - Thesis: *Statistical Learning and Autism-Related Communication Difficulties.*
Claudia Sehl
Zack Cohen
Sara Jasim
Tyler Dalal

Certificates

Oct 2018 Autism Diagnostic Observation Schedule (ADOS-2) Advanced Research and Clinical Training. University of Michigan. Department of Psychiatry.

Feb 2018 Heartsaver CPR AED (C) Adult, Child, Infant, Exam. Heart and Stroke Foundation of Canada.

Jan 2017 Applied Suicide Intervention Skills Training (ASIST). Trent University, Oshawa, Ontario.

Sept 2016 Accessibilities Training & Workplace Violence and Harassment Training, Trent University, Durham, Oshawa, Ontario.

Academic Positions and Related Activities

2019 – present Western Women in Neuroscience Diversity in STEM Conference Chair, University of Western Ontario.

2017-present Western Women in Neuroscience, University of Western Ontario.

2018-2019 Canadian National Brain Bee Competition, University of Western Ontario.

2017- 2018 UWO (Department of Psychology) Graduate Teaching Assistant for 2800E "Research Methods in Psychology"

2016-2017 Patient mentor in the Ontario Shores Young Adults Transitional Service Unit, Whitby, Ontario.

2016-2017 Exam Proctor, Trent University Exam Center.

2016-2017 Circulation Services Support, Trent University Library.

2015-2017 Academic Mentor for Advanced Statistics and Research Design, Trent University, Oshawa, Ontario.

2015-2017 Executive of Trent Durham Psychology Association (TDPA), Trent University, Oshawa, Ontario.

2015-2016 Big Brothers, Big Sisters of Clarington, Bowmanville, Ontario.

2015-2016 Student Mentor in the Ontario Shores Supportive Education Program (OSSEP),Whitby, Ontario.