Published in final edited form as:

J Autism Dev Disord. 2019 January ; 49(1): 397–403. doi:10.1007/s10803-018-3667-x.

Brief Report: Differences in Multisensory Integration Covary with Sensory Responsiveness in Children with and without Autism Spectrum Disorder

Jacob I. Feldman, MS, PhD^{#1} [student], Wayne Kuang^{#1}, Julie G. Conrad¹, Alexander Tu¹, Pooja Santapuram¹, David M. Simon, BA, PhD^{1,2} [student in Neuroscience], Jennifer H. Foss-Feig, PhD³ [Assistant Professor], Leslie D. Kwakye, PhD⁴ [Assistant Professor], Ryan A. Stevenson, PhD⁵ [Assistant Professor], Mark T. Wallace, PhD^{1,2,7} [Dean of the Graduate School; Professor], Tiffany G. Woynaroski, PhD^{2,6,7} [Assistant Professor]

¹Department of Hearing and Speech Sciences, Vanderbilt University, MCE 8310 South Tower, 1215 21st Avenue South, Nashville, TN 37232

²Vanderbilt Brain Institute, 465 21st Avenue South, Nashville, TN 37232.

³Department of Psychiatry, Seaver Autism Center for Research and Treatment at the Icahn School of Medicine at Mount Sinai, One Gustave Levy Place, Box 1230, New York, NY 10029.

⁴Department of Neuroscience, Oberlin College, Science Center A237, Oberlin College, 119 Woodland St., Oberlin, OH 44074.

⁵Department of Psychology, Brain and Mind Institute at The University of Western Ontario, The Schulich School of Medicine and Dentistry Psychiatry Department and Neuroscience Program, York University Centre for Vision Research, Westminster Hall Room 315e, 361 Windermere Road, London, Ontario, Canada, M5S 3G3.

⁶Department of Hearing and Speech Sciences, Vanderbilt Kennedy Center, Vanderbilt Brain Institute, Vanderbilt University Medical Center MCE 8310 South Tower, 1215 21st Avenue South, Nashville, TN 37232.

⁷Department of Hearing and Speech Sciences, Department of Psychological Sciences, and Department of Psychiatry and Behavioral Sciences, Vanderbilt University; Vanderbilt Kennedy Center; Vanderbilt Kennedy Center Institute; 7110 MRB III BioSci Bldg PMB 407933 465 21st Ave South Nashville, TN 37240.

Correspondence regarding this manuscript may be addressed to Tiffany Woynaroski via email at tiffany.g.woynaroski@vanderbilt.edu, by phone at (615) 878-1709, or by mail at MCE 8310 South Tower, 1215 21st Avenue South, Nashville, TN 37232.

Jacob I. Feldman, MS, CCC-SLP is a PhD student in the Department of Hearing and Speech Sciences at Vanderbilt University. Wayne Kuang, BS; Julie G. Conrad, BS; Alexander Tu, BS; and Pooja Santapuram, BS, were undergraduate students at Vanderbilt University when the work was completed. David M. Simon, PhD, was a PhD student in Neuroscience at Vanderbilt University when the work was completed. Jennifer H. Foss-Feig, PhD, is Assistant Professor in the Department of Psychiatry and faculty member of the Seaver Autism Center for Research and Treatment at the Icahn School of Medicine at Mount Sinai. Leslie D. Kwakye, PhD, is Assistant Professor in the Department of Neuroscience at Oberlin College. Ryan A. Stevenson, PhD, is Assistant Professor in the Department of Psychology, a member of the Brain and Mind Institute at The University of Western Ontario, The Schulich School of Medicine and Dentistry Psychiatry Department and Neuroscience Program, and the York University Centre for Vision Research. Mark T. Wallace, PhD, is Dean of the Graduate School; Professor in the Department of Hearing and Speech Sciences, Department of Psychological Sciences, and Department of Psychiatry and Behavioral Sciences; Investigator in the Vanderbilt Kennedy Center; and member of the Vanderbilt Brain Institute at Vanderbilt University. Tiffany Woynaroski, PhD, CCC-SLP is Assistant Professor in the Department of Hearing and Speech Sciences, Investigator in the Vanderbilt Kennedy Center at Vanderbilt University Medical Center, and member of the Vanderbilt Brain Institute and Vanderbilt University.

These authors contributed equally to this work.

Abstract

Research shows that children with autism spectrum disorder (ASD) differ in their behavioral patterns of responding to sensory stimuli (i.e., sensory responsiveness) and in various other aspects of sensory functioning relative to typical peers. This study explored relations between measures of sensory responsiveness and multisensory speech perception and integration in children with and without ASD. Participants were 8–17 year old children, 18 with ASD and 18 matched typically developing controls. Participants completed a psychophysical speech perception task, and parents reported on children's sensory responsiveness. Psychophysical measures (e.g., audiovisual accuracy, temporal binding window) were associated with patterns of sensory responsiveness (e.g., hyporesponsiveness, sensory seeking). Results indicate that differences in multisensory speech perception and integration covary with atypical patterns of sensory responsiveness.

Keywords

autism; sensory; audiovisual; multisensory integration; temporal binding; speech perception

Investigations carried out by clinically-oriented researchers and sensory neuroscientists have provided important insights into the nature of sensory differences in children with autism spectrum disorder (ASD). This work holds great promise for bridging our understanding of the neurobiological bases of sensory function with observed clinical symptomology (Cascio, Woynaroski, Baranek, & Wallace, 2016). Clinically-oriented researchers have focused on behavioral patterns of responding to sensory stimuli (i.e., sensory responsiveness) in children with ASD. Their findings suggest that three atypical patterns of sensory responsiveness are prominent: reduced or absent behavioral responses to sensory stimuli (i.e., hyporesponsiveness), exaggerated behavioral responses to sensory stimuli (i.e., hyperresponsiveness), and/or unusual fascination with or craving of sensory stimuli (i.e., sensory seeking; Baranek, David, Poe, Stone, & Watson, 2006; Ben-Sasson et al., 2009; Boyd et al., 2010; Liss, Saulnier, Fein, & Kinsbourne, 2006; Miller, Anzalone, Lane, Cermak, & Osten, 2007). These atypical patterns of sensory responsiveness have been reported for stimuli presented in a number of sensory modalities (e.g., vision, hearing, touch).

In a parallel line of research, sensory neuroscientists have examined processing of input to multiple sensory modalities. In regards to vision and hearing, individuals with ASD display behavioral enhancements in the perception of simple stimuli (e.g., perception of shapes, detection of pitch in simple tones) and behavioral deficits in the perception of complex or social stimuli (e.g., detection of visual contrasts, detection of pitch in sentences; accuracy in the identification of visual speech; see Baum, Stevenson, & Wallace, 2015 for a review). More recent work has focused on multisensory integration (i.e., the ability to perceive/respond to input from multiple modalities at once, such as the auditory and visual components of speech; see Stevenson et al., 2014a for a review of neuroscientific measurement techniques). Much of this work has focused on the perception of audiovisual stimuli in children with ASD (e.g., Bebko, Weiss, Demark, & Gomez, 2006; Iarocci,

Rombough, Yager, Weeks, & Chua, 2010; Smith & Bennetto, 2007; see Beker, Foxe, & Molholm, 2018 for a recent review). Particular emphasis has been placed on temporal binding, defined as the tendency to perceive multisensory stimuli that occur within a relatively short window of time as originating from a unitary perceptual event (Meredith, Nemitz, & Stein, 1987; Powers, Hillock, & Wallace, 2009). A number of studies have now shown that children with ASD bind auditory and visual stimuli over longer periods or “wider windows” of time than their typically developing (TD) peers (Foss-Feig et al., 2010; Kwakye, Foss-Feig, Cascio, Stone, & Wallace, 2011; Stevenson et al., 2014b; Woynaroski et al., 2013). Similar to findings for unisensory processing (i.e., the ability to respond to input in one sensory modality, such as audition or vision, alone), this extended window of temporal binding may be more pronounced for the integration of more complex audiovisual stimuli such as speech (see Stevenson et al., 2016 for a review).

Despite neuroscientists and clinicians having a shared interest in sensory differences in children with ASD, there have been surprisingly few studies that relate empirically derived measures of sensory and multisensory function to caregiver and clinical reports of sensory responsiveness (Cascio et al., 2016). Some work suggests that there are links between these aspects of sensory function, but these findings are limited. Associations have been found between sensory responsiveness and unisensory perception (i.e., touch and hyper-/hyporesponsiveness; Cascio, Gu, Schauder, Key, & Yoder, 2015; Foss-Feig, Heacock, & Cascio, 2016) and between sensory responsiveness in one sensory domain and multisensory perception (i.e., auditory sensory responsiveness and perception of audiovisual illusions; Woynaroski et al., 2013). However, no associations were found between integration of simple audiovisual stimuli (i.e., flashes and beeps) and a self-report measure of sensory responsiveness in one recent study of adults with and without ASD (Poole, Gowen, Warren, & Poliakoff, 2017). No study to date has comprehensively evaluated the extent to which differences in sensory responsiveness relate to differences in perception of complex auditory, visual, and audiovisual stimuli (i.e., speech) in children on the autism spectrum. The present study thus explored whether several aspects of speech perception and integration relate to patterns of atypical sensory responsiveness (hyporesponsiveness, hyperresponsiveness, and sensory seeking), as assessed by clinical measures, in children with ASD and TD controls.

Methods

The Vanderbilt University Institutional Review Board approved recruitment and study procedures. Parents provided written informed consent, and participants provided written assent prior to participation in the study. All children were compensated for participating.

Participants

Participants included 18 children with ASD and 18 TD controls (partially overlapping with the samples from Foss-Feig et al. 2010; Kwakye et al. 2011; entirely overlapping with the sample from Woynaroski et al., 2013). Eligibility criteria for inclusion in the study were: (a) chronological age between 8 and 17 years; (b) full-scale and verbal IQ standard scores greater than or equal to 70 on the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999); (c) normal hearing and normal or corrected-to-normal vision per parent report; (d) no

history of seizure disorders; (e) completion of 80% of trials on multisensory speech perception tasks; and (f) susceptibility to the McGurk illusion as demonstrated by report of at least one perceived fusion on the McGurk task (see below).

Additional eligibility criteria for children with ASD included: (a) diagnosis of Autistic Disorder, Asperger's Disorder, or Pervasive Developmental Disorder - Not Otherwise Specified according to DSM-IV-TR (APA, 2000) criteria, as confirmed by research-reliable administrations of the Autism Diagnostic Observation Schedule Module 3 (ADOS; Lord et al., 2000) and Autism Diagnostic Interview-Revised (ADI-R; Lord, Rutter, & Le Couteur, 1994), as well as the clinical judgment of a licensed psychologist and (b) no diagnosed genetic disorders (e.g., Fragile X, tuberous sclerosis).

Additional eligibility criteria for TD participants included: (a) parent report of ASD symptoms below the screening threshold on the Lifetime Version of the Social Communication Questionnaire (SCQ; Rutter, Bailey, & Lord, 2003); (b) no immediate family members with diagnoses of ASD; (c) no history of neurological conditions; (d) no prior history or present indicators of psychiatric conditions; and (e) no diagnosed learning disorders. See Table 1 for descriptive group information. ASD and TD groups did not significantly differ in sex, chronological age, or IQ.

Psychophysical Measures of Multisensory Speech Perception and Integration

All participants completed an experimental task that utilized the McGurk illusion to assess several aspects of multisensory speech perception and integration (see Woynaroski et al., 2013 for further detail). Participants viewed video recordings of a young woman saying four syllables: “ba,” “da,” “ga,” and “tha.” These video recordings were presented in four conditions: as an auditory-only stimulus, as a visual-only stimulus (i.e., lip-reading), as a congruent audio-visual stimulus (i.e., same syllable heard and seen spoken), and as an incongruent audio-visual stimulus. In the incongruent audio-visual condition, McGurk stimuli were created by pairing the auditory stimulus “ba” with the discrepant visual stimulus “ga.” This combination facilitates a “fused” percept (i.e., “da” or “tha”; McGurk & MacDonald, 1976). The timing of the auditory “ba” and visual “ga” stimuli was manipulated to evaluate the effects of temporal asynchrony on integration. In addition to a standard synchronous presentation (i.e., 0 ms stimulus onset asynchrony [SOA]), the visual stimulus preceded the auditory stimulus at the following SOAs: 33, 66, 100, 166, 233, and 300 ms.

Accuracy (percent correct identification) was calculated for the auditory-only, visualonly and congruent audio-visual conditions. For the incongruent audio-visual (i.e., McGurk) condition, the individual rates of reported fusion were calculated at each SOA and used to derive temporal binding windows. Temporal binding windows were derived for each child by fitting the rates of reported fusion across SOAs to a psychometric function using the *glmfit* function in MATLAB (Powers et al., 2009; Wallace & Stevenson, 2014) and determining the SOA at which participants fused the auditory and visual stimuli (i.e., reported perceiving the McGurk illusion) on 75% or more of the trials, after normalizing the data (i.e., setting the maximum value to 100%; see Figure 1).

Clinical Measures of Sensory Responsiveness

Two parent report measures were utilized to measure children's sensory responsiveness: (a) the Sensory Experiences Questionnaire (Baranek et al., 2006) and (b) the Sensory Profile Caregiver Questionnaire (Dunn, 1999). Composite scores of hyporesponsiveness (referred to as "poor registration" on the Sensory Profile), hyperresponsiveness (referred to as "sensory sensitivity" on the Sensory Profile), and sensory seeking were calculated for each participant by averaging z-scores for relevant subtests from the Sensory Experiences Questionnaire and the Sensory Profile. Composite scores were used to increase the stability, and thereby to potentially boost the predictive validity, of indices of sensory responsiveness (Rushton, Brainerd, & Pressley, 1983; Yoder & Symons, 2010). A summary of constructs, measures, and metrics used in analyses is provided in Table 2.

Analysis

Multiple imputation was used to handle missing data (ranging from 0 – 27.8% across variables used in analysis). Briefly, multiple imputation involved (a) generation of 40 data sets with plausible values for missing data points, (b) analysis of each filled-in data set, and (c) pooling of the information from the multiple data sets into a single result. Plausible values are generated according to the association of variables with missing data to other variables with observed scores. This method is preferable to traditional methods for dealing with missing data (e.g., listwise deletion, single imputation) because it prevents loss of information related to missing data, reduces bias, improves parameter estimates, and preserves statistical power to detect effects of interest (Enders, 2013; Enders, Baraldi, & Cham, 2014; see Enders, 2010 for additional information regarding this approach). Participants with missing data were similar to participants without missing data (e.g., did not significantly differ in diagnostic status, chronological age, or verbal IQ; all p values $> .1$).

In preliminary analyses, independent samples t-tests were conducted to evaluate between-group differences in sensory responsiveness. A series of regression analyses was then carried out to evaluate the nature of the associations between metrics of multisensory speech perception and integration and metrics of sensory responsiveness. For each analysis, the psychophysics metric of interest (e.g., temporal binding window) was first entered as a predictor of the relevant metric of sensory responsiveness (e.g., hyporesponsiveness) to evaluate the strength and direction of the association across ASD and TD groups. Then, group and the interaction term for the group*psychophysics metric of interest were entered to determine whether associations were moderated by (i.e., varied according to) group. Note that the aforementioned models accounted/controlled for significant between-diagnostic group differences in sensory function, as group was included (along with the psychophysics predictor and the group*psychophysics predictor product term) as an independent variable in all regression models testing moderated effects. Significance tests were not corrected for multiple comparisons, as these analyses were exploratory in nature.

Results

Preliminary Tests of Between-Diagnostic Group Differences

Between-group comparisons on multisensory metrics have previously been reported for this sample ([BLINDED FOR REVIEW]). As detailed in the [BLINDED FOR REVIEW] report, children with ASD, on average, showed reduced visual only and congruent audio-visual speech perception, as well as wider temporal binding windows for audio-visual speech, in comparison to their TD peers. Consistent with the prior literature (see Ben-Sasson et al., 2009), groups additionally differed in mean levels of sensory responsiveness, with the ASD group scoring significantly higher in hyporesponsiveness ($t = 6.44$, $d = 2.15$, $p < 0.001$), hyperresponsiveness ($t = 7.20$, $d = 2.40$, $p < 0.001$), and sensory seeking ($t = 4.00$, $d = 1.33$, $p < 0.001$) relative to TD controls.

Associations Between Multisensory Speech Perception and Integration and Sensory Responsiveness

Many metrics of multisensory speech perception and integration were significantly correlated with patterns of sensory responsiveness (see Table 3). None of the associations were moderated by group (p values $> .4$). Effect sizes for significant correlations were generally moderate to large in magnitude.

Hyporesponsiveness was negatively correlated with perceptual accuracy for auditoryonly, visual-only, and matched audiovisual speech (e.g., Figure 2A). Hyperresponsiveness was negatively correlated with accuracy in the visual-only and matched audiovisual conditions, and sensory seeking was negatively correlated with accuracy in the matched audiovisual condition. Thus, reduced perceptual accuracy for speech stimuli as measured with psychophysical tasks was associated with more atypical patterns of sensory responsiveness.

In regard to the measures derived from the incongruent audio-visual condition, audiovisual temporal acuity as indexed via the temporal binding window was positively correlated with both hyporesponsiveness and sensory seeking (e.g., Figure 2B). Thus, poorer audio-visual temporal acuity (i.e., wider temporal binding windows) was associated with more atypical patterns of sensory responsiveness, specifically hyporesponsiveness and sensory seeking.

Discussion

The purpose of this study was to investigate whether impaired performance on a task indexing the perception and integration of audiovisual speech stimuli is related to atypical sensory responsiveness. Results indicate that reduced visual and audio-visual speech identification accuracy and poorer temporal acuity for audiovisual speech both are associated with more atypical sensory responsiveness. To our knowledge, these results are the first to link patterns of sensory responsiveness to psychophysical measures of multisensory speech perception and integration. These associations were most frequently observed and greatest in magnitude for hyporesponsiveness, the pattern of sensory responsiveness that is most prevalent in and specific to ASD (Baranek et al., 2006). Some aspects of multisensory speech perception were also correlated with sensory seeking, a pattern of sensory responsiveness that frequently cooccurs with hyporesponsiveness

(Ausderau et al., 2014; Liss et al., 2006), and hyperresponsiveness; those effect sizes were generally smaller in magnitude. None of the observed associations varied according to diagnostic status.

There are several limitations to this study. First, our sample was small and largely limited to older and relatively higher-functioning children with ASD, who could attend to our psychophysical tasks and actively report their perception for an extended period of time. Further work is needed to determine to extent to which the present results will generalize to the broader population of children with ASD and/or to other clinical populations. Additionally, significance tests were not corrected for multiple comparisons, as these analyses were exploratory in nature.

Finally, although we have preliminary evidence for an association between atypical perception and integration of audiovisual speech and atypical sensory responsiveness, we cannot draw any inferences about directionality or causality between these aspects of sensory function at this time. We put forth here two different hypotheses relevant to the pattern of results that we have observed, specifically in regard to the robust relations between hyposensitiveness and metrics of multisensory speech perception. First, young children who have difficulty with the perception and integration of audiovisual stimuli over time may orient less to the source of these stimuli, resulting in a behavioral pattern of hyposensitiveness. Alternatively, it is possible that young children who are hyposensitive, by virtue of reduced or absent orienting towards sensory stimuli, over time acquire difficulties in integrating and perceiving such stimuli.

The present results extend prior work showing links between indices of sensory functioning and broader autism symptomatology (e.g., Patten, Watson, & Baranek, 2014; Righi et al., 2018; Watson et al., 2011; Woynarowski et al., 2013). Given these observed associations, clinically-oriented researchers and sensory neuroscientists have suggested that interventions targeting improvements in sensory function may lead to broad improvements in other areas of functioning in individuals with ASD (e.g., cognitive, linguistic, social, or adaptive abilities; Cascio et al., 2016). Unfortunately, at present there is limited evidence that any approach to intervention yields improvements in sensory responsiveness and/or multisensory integration, let alone broader ASD symptomatology, in children with ASD (see Barton, Reichow, Schnitz, Smith, & Sherlock, 2015 for a review). Further developing our understanding of the mechanistic link between temporal acuity of multisensory integration and accuracy of speech perception with atypical sensory responsiveness may inform how and when we might best intervene upon sensory differences in children with ASD. There is a pressing need for further research in this area.

Despite these limitations, the present results advance our understanding of how differences in sensory function relate across levels of analysis – between data gathered by clinicians and those more commonly gathered by sensory neuroscientists. This study provides preliminary evidence that patterns of sensory responsiveness covary with psychophysical measures of multisensory perception and integration. Future work is needed to establish causal links and to identify best clinical practices for these differences in sensory function in children with ASD.

Acknowledgments

This work was supported by NIH U54 HD083211 (PI: Dykens), the Wallace Foundation, the Simons Foundation Autism Research Initiative, a Marino Autism Research Institute Discovery Grant (PI: Mark T. Wallace), a National Institute of Child Health and Human Development T32 HD07226 and Dennis Weatherstone Pre-doctoral Fellowship for Jennifer H. Foss-Feig, a Meharry-Vanderbilt Alliance Training Grant for Leslie D. Kwakye, and by CTSA award No. KL2TR000446 for Tiffany G. Woynaroski from the National Center for Advancing Translational Sciences. Ryan A. Stevenson is funded by a Canadian Natural Science and Engineering Research Counsel Discovery Grant (RGPIN-2017-04656), a Social Sciences and Humanities Research Counsel Insight Grant (435-2017-0936), and the University of Western Ontario Faculty Development Research Fund. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the funding agencies. The authors declare no competing interests.

TGW, MTW, JHF, and LDK posed the research questions and collected the original data. TGW, JIF, WK, AT, JGC, and PS scored, entered, and organized the data. TGW, JIF, WK, DMS, RAS, and MTW analyzed the data, interpreted the results, and drafted the manuscript. All authors read and approved the final manuscript.

References

- American Psychiatric Association (2000). *Diagnostic and Statistical Manual of Mental Disorders-IV-TR* Washington, DC: APA.
- Ausderau K, Sideris J, Furlong M, Little LM, Bulluck J, & Baranek GT (2014). National survey of sensory features in children with ASD: Factor structure of the sensory experience questionnaire (3.0). *Journal of Autism and Developmental Disorders*, 44, 915–925. 10.1007/s10803-013-1945-1 [PubMed: 24097141]
- Baranek GT, David FJ, Poe MD, Stone WL, & Watson LR (2006). Sensory Experiences Questionnaire: Discriminating sensory features in young children with autism, developmental delays, and typical development. *Journal of Child Psychology and Psychiatry*, 47, 591–601. 10.1111/j.1469-7610.2005.01546.x [PubMed: 16712636]
- Barton EE, Reichow B, Schnitz A, Smith IC, & Sherlock D (2015). A systematic review of sensory-based treatments for children with disabilities. *Research in Developmental Disabilities*, 37, 64–80. 10.1016/j.ridd.2014.11.006 [PubMed: 25460221]
- Baum SH, Stevenson RA, & Wallace MT (2015). Behavioral, perceptual, and neural alterations in sensory and multisensory function in autism spectrum disorder. *Progress in Neurobiology*, 134, 140–160. 10.1016/j.pneurobio.2015.09.007 [PubMed: 26455789]
- Ben-Sasson A, Hen L, Fluss R, Cermak SA, Engel-Yeger B, & Gal E (2009). A metaanalysis of sensory modulation symptoms in individuals with autism spectrum disorders. *Journal of Autism and Developmental Disorders*, 39, 1–11. 10.1007/s10803-008-0593-3 [PubMed: 18512135]
- Cascio CJ, Gu C, Schauder KB, Key AP, & Yoder P (2015). Somatosensory event-related potentials and association with tactile behavioral responsiveness patterns in children with ASD. *Brain Topography*, 28, 895–903. 10.1007/s10548-015-0439-1 [PubMed: 26016951]
- Cascio CJ, Woynaroski T, Baranek GT, & Wallace MT (2016). Toward an interdisciplinary approach to understanding sensory function in autism spectrum disorder. *Autism Research* 9, 920–925. 10.1002/aur.1612 [PubMed: 27090878]
- Dunn W (1999). *The Sensory Profile: User's manual* San Antonio, TX: Psychological Corporation.
- Enders CK (2010). *Applied missing data analysis* New York, NY: Guilford Press.
- Enders CK (2013). Dealing with missing data in developmental research. *Child Development Perspectives*, 7, 27–31. 10.1111/cdep.12008
- Enders CK, Baraldi AN, & Cham H (2014). Estimating interaction effects with incomplete predictor variables. *Psychological Methods*, 19, 39–55. 10.1037/a0035314 [PubMed: 24707955]
- Foss-Feig JH, Heacock JL, & Cascio CJ (2012). Tactile responsiveness patterns and their association with core features in autism spectrum disorders. *Research in Autism Spectrum Disorders*, 6, 337–344. 10.1016/j.rasd.2011.06.007 [PubMed: 22059092]
- Foss-Feig JH, Kwakye LD, Cascio CJ, Burnette CP, Kadivar H, Stone WL, & Wallace MT (2010). An extended multisensory temporal binding window in autism spectrum disorders. *Experimental Brain Research*, 203, 381–389. doi: 0.1007/s00221-010-2240-4 [PubMed: 20390256]

- Bebko JM, Weiss JA, Demark JL, & Gomez P (2006). Discrimination of temporal synchrony in intermodal events by children with autism and children with developmental disabilities without autism. *Journal of Child Psychology and Psychiatry*, 47, 88–98. 10.1111/j.1469-7610.2005.01443.x [PubMed: 16405645]
- Kwakye LD, Foss-Feig JH, Cascio CJ, Stone WL, & Wallace MT (2011). Altered auditory and multisensory temporal processing in autism spectrum disorders. *Frontiers in Integrative Neuroscience*, 4 1–11. 10.3389/fnint.2010.00129
- Liss M, Saulnier C, Fein D, & Kinsbourne M (2006). Sensory and attention abnormalities in autistic spectrum disorders. *Autism*, 10, 155–172. 10.1177/1362361306062021 [PubMed: 16613865]
- Lord C, Risi S, Lambrecht L, Cook E Jr., Leventhal B, DiLavore P, Pickles A, & Rutter M (2000). Autism diagnostic observation schedule – generic: a standard measure of social and communication deficits associated with the spectrum of autism. *Journal of Autism and Developmental Disorders*, 30, 205–223. [PubMed: 11055457]
- Lord C, Rutter M, & Le Couteur A (1994). Autism diagnostic interview-revised: a revised version of a diagnostic interview for caregivers of individuals with possible pervasive developmental disorders. *Journal of Autism and Developmental Disorders*, 24, 659–685. [PubMed: 7814313]
- McGurk H, & MacDonald J (1976). Hearing lips and seeing voices. *Nature*, 264, 746–748. [PubMed: 1012311]
- Meredith MA, Nemitz JW, & Stein BE (1987). Determinants of multisensory integration in superior colliculus neurons. I. Temporal factors. *The Journal of Neuroscience*, 7, 3215–3229. [PubMed: 3668625]
- Patten E, Watson LR, & Baranek GT (2014). Temporal synchrony detection and associations with language in young children with ASD. *Autism Research and Treatment*, 2014, 1–8. doi: 10.1155/2014/678346
- Boyd BA Baranek GT, Sideris J, Poe MD, Watson LR, Patten E, Miller H (2010) Sensory features and repetitive behaviors in children with autism and developmental delays. *Autism Research*, 3, 78–87, 10.1002/aur.124 [PubMed: 20437603]
- Poole D, Gowen E, Warren PA, & Poliakoff E (2017). Brief report: Which came first? Exploring crossmodal temporal order judgements and their relationship with sensory reactivity in autism and neurotypicals. *Journal of Autism and Developmental Disorders*, 47, 215–223. 10.1007/s10803-016-2925-z [PubMed: 27704294]
- Powers AR, Hillock AR, & Wallace MT (2009). Perceptual training narrows the temporal window of multisensory binding. *The Journal of Neuroscience*, 29, 12265–12274. 10.1523/JNEUROSCI.3501-09.2009 [PubMed: 19793985]
- Righi G, Tenenbaum EJ, McCormick C, Blossom M, Amso D, & Sheinkopf SJ (2018). Sensitivity to audio-visual synchrony and its relation to language abilities in children with and without ASD. *Autism Research*. Advance online publication doi:10.1002/aur.1918
- Rutter M, Bailey A, and Lord C (2003). *SCQ: Social Communication Questionnaire* Los Angeles, CA: Western Psychological Services.
- Stevenson RA, Ghose D, Fister JK, Sarko DK, Altieri NA, Nidiffer AR, ... & Wallace MT (2014a). Identifying and quantifying multisensory integration: a tutorial review. *Brain Topography*, 27, 707–730. 10.1007/s10548-014-0365-7 [PubMed: 24722880]
- Stevenson RA, Segers M, Ferber S, Barense MD, Camarata S & Wallace MT (2016). Keeping time in the brain: Autism spectrum disorder and audiovisual temporal processing. *Autism Research*, 9, 720–738. 10.1002/aur.1566 [PubMed: 26402725]
- Stevenson RA, Siemann JK, Schneider BC, Eberly HE, Woynaroski TG, Camarata SM, & Wallace MT (2014b). Multisensory temporal integration in autism spectrum disorders. *Journal of Neuroscience*, 34, 691–697. 10.1523/JNEUROSCI.3615-13.2014 [PubMed: 24431427]
- Wallace MT, & Stevenson RA (2014). The construct of the multisensory temporal binding window and its dysregulation in developmental disabilities. *Neuropsychologia*, 64, 105–123. 10.1016/j.neuropsychologia.2014.08.005 [PubMed: 25128432]
- Watson LR, Patten E, Baranek GT, Poe M, Boyd BA, Freuler A, & Lorenzi J (2011). Differential associations between sensory response patterns and language, social, and communication measures

in children with autism or other developmental disabilities. *Journal of Speech, Language, and Hearing Research*, 54, 1562–1576. 10.1044/1092-4388(2011/10-0029)

Wechsler D (1999). WASI: Wechsler Abbreviated Scale of Intelligence San Antonio, TX: Harcourt Assessment, Inc.

Woynaroski TG, Kwakye LD, Foss-Feig JH, Stevenson RA, Stone WL, & Wallace MT (2013).

Multisensory speech perception in children with autism spectrum disorders. *Journal of Autism Developmental Disorders*, 43, 2891–2902. 10.1007/s10803-013-1836-5 [PubMed: 23624833]

Iarocci G, Rombough A, Yager J, Weeks DJ, & Chua R (2010). Visual influences on speech perception in children with autism. *Autism*, 14, 305–320. 10.1177/1362361309353615 [PubMed: 20591957]

Miller LJ, Anzalone ME, Lane SJ, Cermak SA, & Osten ET (2007). Concept evolution in sensory integration: A proposed nosology for diagnosis. *The American Journal of Occupational Therapy*, 61, 135–140. [PubMed: 17436834]

Rushton JP, Brainerd CJ, & Pressley M (1983). Behavioral development and construct validity: The principle of aggregation. *Psychological Bulletin*, 94, 18 10.1037/0033-2909.94.1.18

Smith E, & Bennetto L (2007). Audiovisual speech integration and lipreading in autism. *Journal of Child Psychology and Psychiatry*, 48, 813–821. 10.1111/j.1469-7610.2007.01766.x [PubMed: 17683453]

Yoder PJ, & Symons F (2010). *Observational measurement of behavior* New York, NY: Springer Publishing Company.

Figure 1.

Example temporal binding window (TBW) of a study participant. TBWs were derived by fitting the proportion of trials fused across stimulus onset asynchronies (points plotted as blue circles) to a psychometric function using the *glmfit* function in MATLAB (plotted as red line). The TBW is the distance between the maximum (100%) value of the curve and 75% of the maximum (e.g., 179ms).

Figure 2.

Associations between hyporesponsiveness and (A) accuracy for identification of visual only speech and (B) temporal binding windows for audiovisual speech. Gray circles represent participants with autism spectrum disorder. Black circles represent typically developing controls. Children who tend to show diminished behavioral responses to sensory stimuli in everyday settings also tend to (A) show reduced accuracy in identifying visual only speech and (B) bind auditory and visual speech cues over an extended window of time.

Table 1

Means and Standard Deviations of Selected Variables by Group

	ASD <i>M (SD)</i>	TD <i>M (SD)</i>
Age (Years; Months)	12;5 (31.0 mos)	11;5 (23.8 mos)
Sex	16 male; 2 female	15 male; 3 female
Verbal IQ	109.2 (15.9)	113.8 (9.4)
Performance IQ	110.4 (14.5)	105.4 (9.2)
Full Scale IQ	111.2 (16.3)	111.0 (9.2)

Note. ASD = autism spectrum disorder group, TD = typically developing control group. All group comparisons non-significant, p 's > .05.

Table 2**Summary of Constructs, Measures, and Metrics Used in Tests of Associations**

Construct	Metric
<i>Composites of SEQ and SP factors</i>	
Hyporeponsiveness	Average of z-scores for SEQ Hypo and SP Registration
Hyperresponsiveness	Average of z-scores for SEQ Hyper and SP Sensitivity/Reactive
Seeking	Average of z-scores for SEQ Seek and SP Seeking
<i>Metrics derived from psychophysical McGurk illusion task (Woynaroski et al., 2013)</i>	
AV accuracy	Percent correct identification of matched AV syllables
A accuracy	Percent correct identification of auditory-only syllables
V accuracy	Percent correct identification of visual-only syllables
TBW	Width of normalized curve at which rate of McGurk fusion is 75% of participant's maximum for percent reported fusion

Note. TBW = temporal binding window for audiovisual speech stimuli, AV = audiovisual condition, A = auditory-only condition, V = visual-only condition. SEQ = Sensory Experiences Questionnaire. SP = Sensory Profile Caregiver Questionnaire.

Table 3

Correlations between Metrics of Multisensory Integration and Sensory Responsiveness

	Hypo	Hyper	Seeking
AV accuracy	-.53***	-.34*	-.33*
A accuracy	-.38*	-.14	-.22
V accuracy	-.48**	-.44**	-.25
TBW	.44*	.31	.44*

Note. Hypo = hyporesponsiveness aggregate score, Hyper = hyperresponsiveness aggregate score, Seeking = sensory seeking aggregate score, TBW = temporal binding window for audiovisual speech, AV = audiovisual condition, A = auditory-only condition, V = visual-only condition.

*
 $p < 0.05$

**
 $p < 0.01$

 $p < 0.001$