CANDIDATE
REVIEWS

Investigating Atypical Multisensory Processing in Individuals with Autism Spectrum Disorders

Justin Siemann

Blending information from multiple senses together into a perceptual Gestalt is necessary to understand the world. Autism spectrum disorders (ASD) are classically defined by a triad of symptoms, although sensory impairments have been consistently reported as well. Recently, there has been an increased interest in how individuals with ASD combine and integrate information from multiple senses. This article discusses current topics in ASD including neurobiology and sensory impairments with a focus on how atypical processing of multisensory information may be related to the symptoms found in ASD.

Keywords: *Autism, sensory, multisensory integration, temporal processing, audiovisual*

Functional connectivity:
A process used to describe how well brain regions are connected based on the temporal synchronization of the activity between these areas.

Autism Spectrum Disorders: Overview

Autism spectrum disorders are complex neurodevelopmental disorders characterized by repetitive or restricted behaviors, impairments in language and communication, and deficits in social or reciprocal behavior[1]. Currently, it is estimated that 1 in 88 individuals is diagnosed with an ASD and that males are 4 times more likely to be diagnosed than females[2]. Diagnoses of ASD normally occur by 3 years of age, but clinical symptoms may be present earlier in development. Based on the DSM-IV, Autism, Asperger's syndrome, and Pervasive Developmental Disorder Not Otherwise Specified (PDD-NOS) are three disorders that fall within this spectrum. Individuals with autism can be further characterized as either classic or high functioning based on IQ measures. Asperger's syndrome and PDD-NOS differ from autism in that individuals with Asperger's do not have delays in communication and individuals with PDD-NOS either lack impairments in communication or repetitive behaviors or present mild forms of the triad of symptoms[3]. While DSM-IV classification is currently in use it should be recognized that the proposed draft of the DSM-V modifies the definition of ASD.

Neurobiological and Neurophysiological Findings in ASD

In order to investigate possible causes for the symptoms found in autism spectrum disorders, there have been a variety of studies that have focused on determining the neurobiology of ASD. Autism has been characterized by multiple descriptions of atypical structural and functional connections within the brain. A consistent finding is that children with autism tend to have larger brains and greater head circumferences that increase in the first few years of development, then reaches a plateau and growth slows later in life[4, 5]. It is thought that this overgrowth occurs during a critical time period in the development of the frontal and temporal lobes, but does not seem to impact the occipital lobes[6]. This thought stems from atypical morphology demonstrated by an increase in cerebral grey and white matter in the frontal and temporal regions[7]. Another developmental finding in ASD is altered minicolumnar structure. A cortical minicolumn is the fundamental unit in the cortex that is comprised of excitatory pyramidal cells surrounded by inhibitory interneurons[8]. Postmortem studies revealed that in the frontal and temporal lobes, there were increased numbers of minicolumns, pyramidal neurons in the minicolumnar structure, and the overall structure was narrower in individuals with

autism[8, 9]. More excitatory pyramidal neurons along with a greater number of narrower minicolumns could result in over activation of neurons, leading to local cortical connections more likely and long range connections less likely to develop[10]. These neurobiological and structural findings prompted the investigation of possible altered functional connections between specific brain regions in ASD. There have been numerous studies demonstrating a reduced functional connectivity between multiple brain regions in individuals with ASD[11-17]. It was shown that the functional connectivity between Broca and Wernicke's areas, two regions used for speech, was reduced in individuals with ASD compared to typically developed controls[18]. Based on impaired long range connections between regions used for speech processing, this finding provides neurological evidence for possible deficits in communication in ASD.

Autism Spectrum Disorders: Theories

In order to explain the neurobiology along with the symptoms found in this heterogeneous disorder a multitude of theories have been proposed. Weak central coherence, the temporal binding deficit hypothesis, the cortical underconnectivity theory, and an imbalance of excitation/inhibition signaling are relevant theories in explaining disturbances found in ASD[19].

Central coherence is based on the concept that individuals are capable of processing and combining information for a higher level of understanding[20]. The theory of weak central coherence (WCC) states that individuals with autism have impairments in integrating information from a local or detailed perspective to a more global concept[21]. If there is a preference for local over global processing, this may explain aspects of restricted interests and could cause the global meaning of social situations and communication to be impaired. Brock's temporal binding deficit hypothesis tried to explain weak central coherence by looking at potential timing deficits. This theory proposed that long range connections between brain regions may not be as temporally correlated as brain regions that are in closer proximity, which could result in intact local, but impaired global processing[22]. The cortical underconnectivity theory explained this concept in more detail, when functional magnetic resonance imaging (fMRI) studies demonstrated that long distance connections between brain regions were less functionally connected in individuals with autism[18, 23]. The cortical underconnectivity theory has been consistently used to describe atypical processing found in ASD. Just *et al* proposed this theory by using an fMRI sentence comprehension task to demonstrate atypical functional connectivity in individuals with ASD[18]. This theory compliments the previous two theories because it provides a possible reason for global information processing deficits since this type of processing requires the proper timing and integration of information from multiple brain regions[24]. A final explanation is a possible imbalance of the ratio of excitation/inhibition signaling in the brain. This is supported by post-mortem studies in ASD patients demonstrating an increased number of excitatory pyramidal cells[4, 10, 25]. While no one theory can explain all of the symptoms, there are aspects from all of these theories that may lend to greater insights in explaining the impairments that are seen in individuals with ASD.

Sensory Impairments in ASD

In addition to the three classical symptoms that impact individuals with autism, sensory abnormalities have been consistently observed and reported. Sensory dysfunction is not one of the classic symptoms of autism spectrum disorders, yet it is found to impact up to 85% of individuals with ASD[26]. Kanner first reported children with autism spectrum disorders to have sensory disruptions and to date there have been a number of studies demonstrating atypical sensitivity to sensory stimuli[26, 27]. Individuals can be hyper- or hyposensitive to a variety of different stimuli spanning multiple modalities[28, 29]. Using a visual stimulus as an example, individuals with ASD may immediately cover their eyes or stare at bright lights for long periods of time, depending on the individual's sensitivity to the stimulus. This dysfunction can be further classified as either sensory aversion or sensory seeking behavior. Depending on the type of behavior, individuals with autism spectrum disorders may be highly sensitive to or engaged in stimuli that may be considered mundane. Based on these observations, there have been several studies that have correlated sensory impairments with ASD severity[30-33]. Of all the sensory modalities impacted, dysfunctions in the visual and auditory domains have been studied most extensively. One reason for why this may be the case is that these modalities are needed for communication as well as understanding aspects of social behavior. A consistent finding is that individuals with ASD tend to perform well on visual tasks that require the processing of individual features[34, 35]. For example, individuals with ASD can excel on the Embedded Figures and Block Design tasks which are timed and require the identification of smaller objects within a larger figure or the recreation

of a detailed pattern using a set of blocks[20, 21], respectively. While there are reports of enhanced performance on tasks requiring the identification of specific features there have been observations demonstrating impaired global processing when these local features are needed to be combined. For instance, individuals with autism typically are less accurate in identifying biological motion, motion coherence, and visual form compared to controls[36-38]. An interesting finding from these studies however, was that while the high functioning autism group showed deficits in these areas, individuals with Asperger's syndrome performed as well as typically developed individuals, which speaks to the heterogeneity of ASD[37-38]. Similar to the findings in the visual domain, it is known that depending on the task, individuals with ASD perform atypically compared to controls in the auditory domain as well[39]. For example, it has been shown that individuals with ASD tend to excel on tasks that require pitch discrimination specifically of musical tones[40, 41].

Enhanced visual and auditory discrimination to detailed information, yet overall impaired global processing in these modalities are consistent findings in ASD. Communication and behaving in social contexts require a high level of global processing and if individuals with ASD have deficits in this type of processing this could result in information being lost or improperly understood. Besides the possible impaired processing, both communication and social behaviors require the appropriate combination of sensory information from multiple modalities. Based on these observations and studies describing unisensory dysfunction in ASD, there has been an increased focus in determining how multisensory integration may be impacted when sensory stimuli are combined.

Multisensory Integration and Temporal Processing

Multisensory integration can be described as the merging of sensory information from different modalities[42]. Studies have shown that the combination of information from multiple senses can produce behavioral enhancements that can increase accuracy and reduce reaction times[43]. Three principles: space, time, and effectiveness are used to describe multisensory integration[43]. Stimuli from different modalities that are presented in close temporal and/or spatial proximity can result in a maximal multisensory gain[44, 45]. The enhancement seen in behavior from the combination of multiple stimuli compared to one of the sensory stimuli presented alone describes multisensory gain[43]. One effective way to measure multisensory integration is by using cross modal illusions. These illusions can produce interesting behavioral responses based on how one modality affects another. For example, the sound induced flash illusion demonstrates that the auditory domain can alter the visual information that is perceived by individuals[46]. In this illusion when two auditory beeps are played in close temporal proximity to a single visual flash, most individuals perceive multiple visual flashes[46, 47]. Also, it was shown that as the presentation of the second beep is further delayed in time, participants are less likely to perceive the illusion[48]. Therefore, this illusion not only utilizes the temporal principle of multisensory integration, but also demonstrates the concept of a multisensory temporal binding window (TBW). The multisensory TBW can be described as the time interval in which two cross modal stimuli are bound together as a single unified perceived event[49].

It was demonstrated that individuals with ASD performed comparable to typically developed controls for the sound induced illusion, which illustrates that there is intact multisensory integration for simple cross modal stimuli[49]. However, using this illusion, it appears that children with ASD have an extended temporal binding window[50, 51]. Foss-Feig *et al* showed that individuals with ASD perceived this illusion more often when the presentations of the second beep were delayed for longer periods of time[51]. This study demonstrated a multisensory temporal binding window for individuals with ASD that was almost twice as wide as that of typically developed controls. An extended TBW and overall atypical temporal processing could impact communication and the proper understanding of social behaviors, both of which are known to be impaired in autism spectrum disorders. Importantly, it is known that the multisensory temporal binding windows tend to be wider for children in general and it is possible to narrow the TBW with the implementation of multisensory training paradigms[52, 53]. The plasticity of the TBW may allow for future developments of remediation tools for individuals with ASD.

In general, there have been a variety of studies supporting the findings of temporal deficits when individuals with ASD are asked to process multisensory information[54, 55]. Bebko *et al* simultaneously showed children identical videos on two monitors with the only difference being that one of the video tracks was temporally delayed[55]. This study demonstrated that while typically developed children preferentially looked at the videos that were synchronous, children with autism did not have a preference looking at either video, specifically when the stimuli were

speech related. This suggests that the ASD group may not have noticed that one of the videos was temporally out of synchrony, which was why there was no preferential looking for this group. If long range connections between brain regions in ASD are not as temporally correlated as in typically developed individuals then this could explain some of these results especially when more complex stimuli such as speech were used. Overall, these findings suggest that there are multisensory and temporal deficits in autism spectrum disorders, which will likely have a major impact on communication and speech comprehension.

Communication in ASD

The integration of visual and auditory information makes speech naturally, multisensory. With the known impairments of communication in autism, speech and audiovisual integration have been greatly studied topics. It has been shown that individuals with ASD tend to perform worse on audiovisual tasks that use human faces and voices, but perform typically on tasks using non-human stimuli[56]. One task that uses human speech stimuli to measure multisensory integration is the McGurk effect. In this illusion, participants see an individual's face and lips move to form the utterance of /ga/, while simultaneously hearing the utterance /ba/ which tends to cause participants to report the perception of hearing /da/[57]. The McGurk effect can be thought of as a measure of multisensory integration because the McGurk percept of /da/ represents a fusion of both visual and auditory information. Similar to the sound induced flash illusion the McGurk effect is temporally restricted[58]. Multiple studies have shown that children with ASD tend to perceive the McGurk illusion less often than typically developed individuals[59, 60]. This would suggest a possible impairment in multisensory integration since the fused percept was reported less often. An interesting finding however was that adolescents and adults with ASD perceived this illusion as often as typically developed individuals, which suggests that these impairments may improve over time[60, 61].

In addition to a decreased McGurk percept, studies have found that children with ASD tend to perform worse on the visual only condition[59]. This is demonstrated by an impaired ability to lip read, which would mean that individuals with ASD may not benefit from the added visual information especially in a noisy environment in order to understand speech appropriately[62, 63]. Smith *et al* presented individuals with sentences within varying levels of noise and participants were asked to identify specific words when the words were only heard or were seen and heard simultaneously[62]. This study demonstrated that individuals with ASD performed typically compared to controls on the auditory only condition, but were worse at identifying words when both audio and visual information were presented. Impaired multisensory and audiovisual integration in noisy environments, similar to those in the real world, could be one explanation for the communication impairments that are found in ASD. Recently, it has been shown that throughout typical development children can improve on speech in noise tasks[64]. In addition to this finding it was demonstrated that after training on a lip reading paradigm, individuals with ASD reported the McGurk percept as often as controls[59]. These findings provide evidence that this type of training may be another possible remediation tool for individuals with ASD, which may be the most beneficial if implemented earlier during development.

Overall, it has been shown that there are multiple levels of sensory dysfunction in autism spectrum disorders. Not only are there unisensory deficits, but multisensory impairments are also apparent. Atypical multisensory and temporal processing have been most evident in individuals with ASD especially as the stimuli become more complex and related to language. As studies have further characterized this sensory dysfunction, a few examples of possible remediation tools to improve multisensory integration, temporal processing, and speech comprehension have also been described. Multiple behavioral findings have described atypical unisensory and multisensory processing in ASD, which have been insightful in order to better understand this disorder.

Concluding Remarks

ASD is a heterogeneous neurodevelopmental disorder that impacts many aspects of an individual's life. Although multiple reports have described atypical structural and functional connections in ASD, there have not been many neurophysiological studies investigating deficits in multisensory integration and the brain regions that are potentially impacted. Russo *et al* published one of the first studies describing impairments in multisensory integration using EEG measures. This investigation demonstrated that multisensory integration within individuals with ASD was present specifically at later time intervals compared to typically developed individuals[65]. This further suggests that individuals with ASD are capable of integrating stimuli from

multiple modalities, yet temporal impairments are still evident. This study again supports the various findings of atypical multisensory and temporal processing. Based on functional imaging studies with typically developed individuals, one brain region that has been implicated in multisensory integration and temporal processing is the superior temporal sulcus[66-69]. This makes this region a potential area of interest in investigating multisensory impairments in ASD. Although there have been few neurophysiological studies describing multisensory and temporal processing in autism spectrum disorders, this allows for the opportunities of innovative research studies to be pursued.

The primary goal of this review was not only to give an overview of autism spectrum disorders and theories that have been used to explain these disorders, but also to specifically demonstrate how impairments in multisensory integration and temporal processing may relate to the common symptoms that characterize ASD. There have been numerous findings of atypical processing and sensitivity to unisensory stimuli spanning a variety of modalities. By studying how combinations of sensory stimuli are perceived, investigators have been able to further characterize the impairments in multisensory integration in individuals with ASD. Deficits in multisensory integration have led to findings of impaired temporal processing, which have generated an increased interest on how this could impact symptoms in ASD such as communication. This knowledge has generated behavioral studies focused on modulating audiovisual and speech stimuli. In addition to characterizing ASD behaviorally, there have been a variety of studies devoted to determining the neurobiology of ASD and how atypical development may impact connections and activity between brain regions in these disorders. A large number of neurophysiological studies have now characterized structural and functional impairments in individuals with ASD, but only a few have investigated multisensory processing. Additional studies that help to characterize atypical multisensory processing will not only improve our understanding of the impairments, but will also raise the possibility of developing better remediation tools for individuals with ASD in the future.

References

1. APA (2000). Diagnostic and Statistical Manual of Mental Disorders DSM-IV-TR. In. Washington, D.C: American Psychiatric Association.

2. CDC (2008). Prevalence of autism spectrum disorders – Autism and developmental disabilities monitory network. In: Morbidity and Mortality Weekly Report Surveillance Summary, pp 1-19. United States: Centers for Disease Control and Prevention

3. DiCicco-Bloom E, Lord C, Zwaigenbaum L, Courchesne E, Dager SR, Schmitz C, Schultz RT, Crawley J and Young LJ (2006). The developmental neurobiology of autism spectrum disorder. The Journal of Neurosci. 26 (26): 6897-6906.

4. Casanova MF (2007). The neuropathology of autism. Brain pathology. 17 (4): 422-433.

5. White S, O'Reilly H and Frith U (2009). Big heads, small details and autism. Neuropsychologia. 47 (5): 1274-1281.

6. Courchesne E, Pierce K, Schumann CM, Redcay E, Buckwalter JA, Kennedy DP and Morgan J (2007). Mapping early brain development in autism. Neuron. 56 (2): 399-413.

7. Courchesne E (2004). Brain development in autism: early overgrowth followed by premature arrest of growth. Ment Retard Dev Disabil Res Rev. 10 (2): 106-111.

8. Casanova MF, Buxhoeveden DP, Switala AE and Roy E (2002). Minicolumnar pathology in autism. Neurology. 58 (3): 428-432.

9. Courchesne E, Redcay E, Morgan JT and Kennedy DP (2005). Autism at the beginning: Microstructural and growth abnormalities underlying the cognitive and behavioral phenotype of autism. Development and Psychopathology. 17 (3): 577-597.

10. Rubenstein JL and Merzenich MM (2003). Model of autism: increased ratio of excitation/inhibition in key neural systems. Genes, brain, and behavior. 2 (5): 255-267.

11. David O, Cosmelli D and Friston KJ (2004). Evaluation of different measures of functional connectivity using a neural mass model. Neuroimage. 21 (2): 659-673.

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

13. Schroeder JH, Desrocher M, Bebko JM and Cappadocia MC (2010). The neurobiology of autism: Theoretical applications. Research in Autism Spectrum Disorders. 4 (4): 555-564.

14. Minshew NJ and Keller TA (2010). The nature of brain dysfunction in autism: functional brain imaging studies. Curr Opin Neurol. 23 (2): 124-130.

15. Hughes JR (2007). Autism: the first firm finding = underconnectivity? Epilepsy Behav. 11 (1): 20-24.

16. Rippon G, Brock J, Brown C and Boucher J (2007). Disordered connectivity in the autistic brain: challenges for the "new psychophysiology". International journal of psychophysiology : official journal of the International Organization of Psychophysiology. 63 (2): 164-172.

17. Belmonte MK, Allen G, Beckel-Mitchener A, Boulanger LM, Carper RA and Webb SJ (2004). Autism and abnormal development of brain connectivity. J Neurosci. 24 (42): 9228-9231.

18. **Just MA, Cherkassky VL, Keller TA and Minshew NJ (2004). Cortical activation and synchronization during sentence**

comprehension in high-functioning autism: evidence of underconnectivity. Brain : a journal of neurology. 127 (Pt 8): 1811-1821.

This study proposes the theory of cortical underconnectivity in ASD, which discusses neurological impairments to describe atypical processing in ASD.

19. Levy F (2007). Theories of autism. The Australian and New Zealand journal of psychiatry. 41 (11): 859-868.

20. Happe F (1999). Autism: cognitive deficit or cognitive style? Trends Cogn Sci. 3 (6): 216-222.

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

22. Brock J, Brown CC, Boucher J and Rippon G (2002). The temporal binding deficit hypothesis of autism. Development and psychopathology. 14 (2): 209-224.

23. Kana RK, Libero LE and Moore MS (2011). Disrupted cortical connectivity theory as an explanatory model for autism spectrum disorders. Phys Life Rev. 8 (4): 410-437.

24. Sgado P, Dunleavy M, Genovesi S, Provenzano G and Bozzi Y (2011). The role of GABAergic system in neurodevelopmental disorders: a focus on autism and epilepsy. Int J Physiol Pathophysiol Pharmacol. 3 (3): 223-235.

25. Di Cristo G (2007). Development of cortical GABAergic circuits and its implications for neurodevelopmental disorders. Clinical genetics. 72 (1): 1-8.

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

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

28. Minshew NJ and Hobson JA (2008). Sensory sensitivities and performance on sensory perceptual tasks in high-functioning individuals with autism. Journal of Autism and Developmental Disorders. 38 (8): 1485-1498.

29. Schoen SA, Miller LJ, Brett-Green BA and Nielsen DM (2009). Physiological and behavioral differences in sensory processing: a comparison of children with autism spectrum disorder and sensory modulation disorder. Frontiers in integrative neuroscience. 3: 29.

30. Kern JK, Trivedi MH, Grannemann BD, Garver CR, Johnson DG, Andrews AA, Savla JS, Mehta JA and Schroeder JL (2007). Sensory correlations in autism. 11 (2): 123-134.

31. Hilton CL, Harper JD, Kueker RH, Lang AR, Abbacchi AM, Todorov A and LaVesser PD (2010). Sensory Responsiveness as a Predictor of Social Severity in Children with High Functioning Autism Spectrum Disorders. Journal of Autism and Developmental Disorders. 40 (8): 937-945.

32. Klintwall L, Holm A, Eriksson M, Carlsson LH, Olsson MB, Hedvall A, Gillberg C and Fernell E (2011). Sensory abnormalities in autism. A brief report. Res Dev Disabil. 32 (2): 795-800.

33. Rogers SJ and Ozonoff S (2005). Annotation: What do we know about sensory dysfunction in autism? A critical review of the empirical evidence. Journal of Child Psychology and Psychiatry. 46 (12): 1255-1268.

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

35. Chen Y, Norton DJ, McBain R, Gold J, Frazier JA and Coyle JT (2012). Enhanced local processing of dynamic visual information in autism: evidence from speed discrimination. Neuropsychologia. 50 (5): 733-739.

36. Blake R, Turner LM, Smoski MJ, Pozdol SL and Stone WL (2003). Visual recognition of biological motion is impaired in children with autism. Psychological science. 14 (2): 151-157.

37. Spencer JV and O'Brien JM (2006). Visual form-processing deficits in autism. Perception. 35 (8): 1047-1055.

38. Tsermentseli S, O'Brien JM and Spencer JV (2008). Comparison of form and motion coherence processing in autistic spectrum disorders and dyslexia. Journal of Autism and Developmental Disorders. 38 (7): 1201-1210.

39. Marco EJ, Hinkley LB, Hill SS and Nagarajan SS (2011). Sensory processing in autism: a review of neurophysiologic findings. Pediatric research. 69 (5 Pt 2): 48R-54R.

40. O'Connor K (2012). Auditory processing in autism spectrum disorder: a review. Neurosci Biobehav Rev. 36 (2): 836-854.

41. O'Riordan M and Passetti F (2006). Discrimination in autism within different sensory modalities. Journal of Autism and Developmental Disorders. 36 (5): 665-675.

42. Meredith MA and Stein BE (1983). Interactions among Converging Sensory Inputs in the Superior Colliculus. Science. 221 (4608): 389-391.

43. Stein BE and Stanford TR (2008). Multisensory integration: current issues from the perspective of the single neuron. Nature reviews Neuroscience. 9 (4): 255-266.

44. Meredith MA and Stein BE (1986). Spatial Factors Determine the Activity of Multisensory Neurons in Cat Superior Colliculus. Brain Res. 365 (2): 350-354.

45. Meredith MA, Nemitz JW and Stein BE (1987). Determinants of Multisensory Integration in Superior Colliculus Neurons .1. Temporal Factors. Journal of Neuroscience. 7 (10): 3215-3229.

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

47. Shimojo S and Shams L (2001). Sensory modalities are not separate modalities: plasticity and interactions. Current opinion in neurobiology. 11 (4): 505-509.

48. Shams L, Kamitani Y and Shimojo S (2002). Visual illusion induced by sound. Brain Res Cogn Brain Res. 14 (1): 147-152.

49. van der Smagt MJ, van Engeland H and Kemner C (2007). Brief report: Can you see what is not there? Low-level auditory-visual integration in autism spectrum disorder. Journal of Autism and Developmental Disorders. 37 (10): 2014-2019.

50. Kwakye LD, Foss-Feig JH, Cascio CJ, Stone WL and Wallace MT (2011). Altered auditory and multisensory temporal processing in autism spectrum disorders. Frontiers in integrative neuroscience. 4: 129.

51. Foss-Feig JH, Kwakye LD, Cascio CJ, Burnette CP, Kadivar H,

Stone WL and Wallace MT (2010). An extended multisensory temporal binding window in autism spectrum disorders. Experimental Brain Research. 203 (2): 381-389.

52. Hillock AR, Powers AR and Wallace MT (2011). Binding of sights and sounds: age-related changes in multisensory temporal processing. Neuropsychologia. 49 (3): 461-467.

53. Powers AR, Hillock AR and Wallace MT (2009). Perceptual Training Narrows the Temporal Window of Multisensory Binding. Journal of Neuroscience. 29 (39): 12265-12274.

54. Nakano T, Ota H, Kato N and Kitazawa S (2010). Deficit in visual temporal integration in autism spectrum disorders. Proceedings Biological sciences / The Royal Society. 277 (1684): 1027-1030.

55. Bebko JM, Weiss JA, Demark JL and 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, and allied disciplines. 47 (1): 88-98.

56. Mongillo EA, Irwin JR, Whalen DH, Klaiman C, Carter AS and Schultz RT (2008). Audiovisual processing in children with and without autism spectrum disorders. J Autism Dev Disord. 38 (7): 1349-1358.

57. Mcgurk H and Macdonald J (1976). Hearing Lips and Seeing Voices. Nature. 264 (5588): 746-748.

58. van Wassenhove V, Grant KW and Poeppel D (2007). Temporal window of integration in auditory-visual speech perception. Neuropsychologia. 45 (3): 598-607.

59. Williams JH, Massaro DW, Peel NJ, Bosseler A and Suddendorf T (2004). Visual-auditory integration during speech imitation in autism. Research in developmental disabilities. 25 (6): 559-575.

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

This study demonstrates that atypical multisensory integration may improve in individuals with ASD throughout development.

61. Keane BP, Rosenthal O, Chun NH and Shams L (2010). Audiovisual integration in high functioning adults with autism. Research in Autism Spectrum Disorders. 4 (2): 276-289.

62. Smith EG and Bennetto L (2007). Audiovisual speech integration and lipreading in autism. Journal of child psychology and psychiatry, and allied disciplines. 48 (8): 813-821.

63. Iarocci G, Rombough A, Yager J, Weeks DJ and Chua R (2010). Visual influences on speech perception in children with autism. Autism : the international journal of research and practice. 14 (4): 305-320.

64. **Ross LA, Molholm S, Blanco D, Gomez-Ramirez M, Saint-Amour D and Foxe JJ (2011). The development of multisensory speech perception continues into the late childhood years. Eur J Neurosci. 33 (12): 2329-2337.**

This study demonstrates that typically developed children improve throughout development on speech in noise tasks, which shows a potential for improvement in multisensory processing.

65. **Russo N, Foxe JJ, Brandwein AB, Altschuler T, Gomes H and Molholm S (2010). Multisensory processing in children with autism: high-density electrical mapping of auditory-somatosensory integration. Autism research : official journal of the International Society for Autism Research. 3 (5): 253-267.**

This is one of the first studies investigating multisensory integration in ASD using EEG methods to determine possible temporal processing impairments.

66. Driver J and Noesselt T (2008). Multisensory interplay reveals crossmodal influences on 'sensory-specific' brain regions, neural responses, and judgments. Neuron. 57 (1): 11-23.

67. Nath AR, Fava EE and Beauchamp MS (2011). Neural correlates of interindividual differences in children's audiovisual speech perception. J Neurosci. 31 (39): 13963-13971.

68. Powers AR, 3rd, Hevey MA and Wallace MT (2012). Neural correlates of multisensory perceptual learning. J Neurosci. 32 (18): 6263-6274.

69. Stevenson RA, VanDerKlok RM, Pisoni DB and James TW (2011). Discrete neural substrates underlie complementary audiovisual speech integration processes. Neuroimage. 55 (3): 1339-1345.

Correspondence: justin.k.siemann@vanderbilt.edu

Further information: http://kc.vanderbilt.edu/multisensory/index.html