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RESEARCH ARTICLE

Links between multisensory processing and autism

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Abstract Autism spectrum disorder is typically associated with social deficits and is often specifically linked to difficulty with processing faces and other socially relevant stimuli. Emerging research has suggested that children with autism might also have deficits in basic perceptual abilities including multisensory processing (e.g., simultaneously processing visual and auditory inputs). The current study examined the relationship between multisensory temporal processing (assessed via a simultaneity judgment task wherein participants were to report whether a visual stimulus and an auditory stimulus occurred at the same time or at different times) and self-reported symptoms of autism (assessed via the Autism Spectrum Quotient questionnaire). Data from over 100 healthy adults revealed a relationship between these two factors as multisensory timing perception correlated with symptoms of autism. Specifically, a stronger bias to perceive auditory stimuli occurring before visual stimuli as simultaneous was associated with greater levels of autistic symptoms. Additional data and analyses confirm that this relationship is specific to multisensory processing and symptoms of autism. These results provide insight into the nature of multisensory processing while also revealing a continuum over which perceptual abilities correlate with symptoms of autism and that this continuum is not just specific to clinical populations but is present within the general population.

Keywords Multisensory · Autism · Auditory · Visual · Temporal

Introduction

According to the Centers for Disease Control (2012), one in every 88 children in the US is diagnosed with autism spectrum disorder. With such a broad prevalence in the population, numerous efforts have focused on identifying the underlying nature of the disorder. While some progress has been made in this area and emerging results suggest that there may be genetic makers (e.g., Xiong et al. 2012), electrophysiological predictors (e.g., Elsabbagh et al. 2012), and potential treatments (see Modi and Young 2012) for autism, there are still many aspects of autism spectrum disorder that are unknown. Moreover, studying autism is not an easy task, given the vast heterogeneity of autistic symptoms and of the severity of the symptoms (e.g., see Miles 2011). Despite this, one direction that has been quite fruitful has been to examine links between autism and specific cognitive processes (see Charman et al. 2011 for a recent discussion). One such link between cognition and autism is that individuals with autism process faces differently (e.g., Dalton et al. 2005; Grelotti et al. 2002; Osterling and Dawson 1994). Specifically, autistic individuals generally have deficits in processing affective content of faces (e.g., Adolphs et al. 2001; Harms et al. 2010 for review), using eye gaze cues to understand what another individual might be thinking or feeling (e.g., Baron-Cohen et al. 1999) and recognizing emotion through

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vocal cues and body movements (Philip et al. 2010). Drawing links between cognition and autism provides exciting possibilities for both cognitive and clinical realms; such research can provide insight into the mechanisms of normal cognitive function and can shed light on the specific deficits that are occurring in disorders so that they might be treated.

While affective and facial deficits have become signature markers of autism, they are not the only cognitive differences that exist between individuals with and without autism. Face perception is a relatively 'high-level' cognitive process that entails several components of 'low-level' processing.[1] Research has found a link between autism and low-level perceptual processing (see Marco et al. 2011 for review); for example, several recent studies have found differences between individuals with and without autism in how their brains respond to stimuli—early evoked responses recorded with electroencephalography (EEG) suggest differences in how low-level visual and/or auditory stimuli are processed (Batty et al. 2011; Hileman et al. 2011; Kwon et al. 2007; Roth et al. 2012). Finding deficits in sensory perception that are tied to autism is potentially very telling given that most 'higher level' forms of cognition rely upon these basic 'low-level' perceptual processes. Further exploring these links may help to ultimately explain some of the other deficits that are typically found with autism, including communication and social cognition difficulties.

One particularly fruitful area to further explore is that of multisensory perception. A fundamental aspect of perception is the ability to bind together information from across multiple modalities (see Alais et al. 2010; Driver and Noesselt 2008 for reviews). Such processing serves as the core means of binding together spatially and temporally coincident information into separable, distinct objects. The integration of multisensory stimuli into objects allows us to not be overwhelmed by the constant input of auditory and visual information and allows us to focus on and selectively attending to a specific object in a noisy environment. For example, when trying to hold a conversation with a specific friend at a noisy party, that friend's speech is identified as unique and belonging to him (as opposed to belonging to the other people talking) through the relationship between the sound of his speech and the movement of his mouth. Moreover, multisensory integration can be crucial for survival; imagine you are trying to cross a street and hear a car horn—being able to bind together the sound of the horn with the appropriate car is nontrivial and can be quite important for your ability to successfully cross the street.

One factor that influences whether or not multisensory stimuli will be bound together into a unified object is whether or not the stimuli occur in close temporal proximity. That is, stimuli presented within a short time frame are more likely to be bound into a multisensory object than stimuli that are far apart in time. Typically, multisensory stimuli will be temporally linked together if they occur within about 150 ms of each other, and this time frame is referred to as the 'temporal window of integration' (see Donohue et al. 2010; Powers et al. 2009; Stein and Stanford 2008; Stone et al. 2001; Zampini et al. 2005). Recent evidence suggests that individuals with and without autism might differ in how they bind together multisensory information. Interestingly, in a study looking at differences in multisensory temporal processing between children with autism and typically developing children, the children with autism were found to have a larger temporal window of integration. Such a broad temporal window would likely produce abnormal binding of multisensory stimuli, with stimuli being linked in time that may not have originated from the same source (Foss-Feig et al. 2010).

In addition to behavioral differences in multisensory processing, neural differences in multisensory processing between children with autism and typically developing children have been observed (Russo et al. 2010). While typically developing children had an enhanced neural response (i.e., an enhanced event-related potential) to the combination of auditory and tactile stimuli, this multisensory neural enhancement was not present in the children with autism (Russo et al. 2010). These results suggest that even with simple stimuli, children with autism are not integrating multisensory information in a typical way and that this lack of neural integration could underlie some of the social-cognitive deficits often observed in children with autism.

One experimental task typically used to examine the dynamics of multisensory temporal integration is a simultaneity judgment task (e.g., Donohue et al. 2010; Powers et al. 2009; Zampini et al. 2005). In this task, multisensory stimuli (e.g., an auditory beep and a visual pattern) are presented over a broad range of stimulus onset asynchronies (SOAs; i.e., different delays between the onset of an auditory stimulus and a visual stimulus). Participants are asked to determine if the auditory and visual stimuli occur at the same time or at different times. This task is designed to yield a point of subjective simultaneity (PSS), which reveals the specific SOA at which participants are most likely perceiving the auditory and visual stimuli as occurring simultaneously. For most people, the PSS is not when the stimuli are physically simultaneous, but rather when the visual stimulus comes slightly (typically less than 50 ms) before the auditory stimulus (Stone et al. 2001; van Eijk et al. 2008).

The newly found link between multisensory processing and autism (reviewed in Marco et al. 2011) opens the door

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[1] We define 'low-level' visual processes as the basic, first steps of perception such as discriminating the orientation of visual stimuli or determining the frequency of an auditory sound, and 'high-level' processing as the identification of a face or speech, or any complex object consisting of multiple types of 'low-level' stimuli.

for much more to be explored. By better understanding the nature of this link, it should be possible to inform both the study of autism and the study of cognition. Here, we pursue this avenue of research and do so with an experimental procedure that has some potential benefits. Specifically, we examine the links between symptoms of autism and the temporal aspects of multisensory processing with an adult population that was not selectively chosen for having, or not having, symptoms of autism. The majority of previous work on multisensory processing in autism has focused on children diagnosed with autism (e.g., Kwakye et al. 2011), which is entirely appropriate given that the earlier the symptoms and deficits appear to emerge, the earlier potential interventions can be performed. Here, though we focus on adult participants that vary along a continuum of the autism spectrum rather than contrasting extreme groups. Although studying group differences is extremely informative (e.g., Baron-Cohen et al. 1999), such designs, by definition, leave out the variability present across the entire population. Because autism is a spectrum disorder with immense variability both within the general population and within those diagnosed with autism, it is worth considering how varying levels of symptoms relate to multisensory processing.

The current goal is to examine variation in multisensory processing in relation to varying levels of symptoms of autism in a relatively large, non-clinical population. To accomplish this goal, we took advantage of an existing experimental protocol in our research laboratory at Duke University. Specifically, as part of this protocol, members of the Duke community are recruited to participate in two experimental phases: an individual differences assessment phase and a behavioral testing phase. We obtained the measures of autism for the current study from the individual differences assessment phase (always conducted on the first visit to the laboratory). This phase consisted of a larger battery of surveys and questionnaires (see "Methods" section and "Appendix"). Our primary dependent measure, a simultaneity judgment task to assess multisensory processing, was obtained from the behavioral testing phase (see "Methods"). As will be discussed below, this experimental protocol provides additional assessments (e.g., measures of video game playing habits and symptoms of ADHD) and additional behavioral tests (e.g., a visual–visual temporal-order judgment task) that we can use to further determine the specificity of our autism and multisensory findings.

Methods

Participants

Data from 101 participants (54 female) from the Duke University community were included in this study (mean age = 21.4 years, SD = 5.28). An additional 16 participants completed the study but were excluded from analysis; 13 due to having an outlying point of subjective simultaneity (see below), and 3 due to not having completed the survey portion of the experiment. All methods and procedures were approved by Duke University's Institutional Review Board. Participants received either course credit or monetary compensation.

General procedure

This experiment stemmed from a larger project conducted in the Duke Visual Cognition Laboratory. On the participants' first visit to the laboratory, they completed an hour-and-a-half long battery of assessments that was primarily composed of self-report questionnaires. One of the assessments was the Autism Spectrum Quotient questionnaire (ASQ; Baron-Cohen et al. 2001). The ASQ is a self-report questionnaire that is commonly used in research as a screening measure for symptoms of autism. The ASQ contains 50 individual questions that make up five subcategories: social skill, attention switching, attention to detail, communication, and imagination. Scores can range from 0 to 50, with higher scores suggesting more symptoms of autism. A score of 32 or more is considered indicative of substantial symptoms, and consultation with a doctor may be suggested (Baron-Cohen et al. 2001). Our a priori hypothesis was that symptoms of autism would correlate with multisensory processing, so, while we had several potential measures available for comparison, we restricted our analyses to this particular scale. The other measures that were obtained from participants are reported in the "Appendix", but note that we only examined the specific measures for which we had a priori hypotheses. The other measures are provided for completeness, but they were not assessed.

In a subsequent visit to the laboratory, participants completed a multisensory simultaneity judgment task that was the primary measure of interest for the current study (described in detail below). This multiple-visit design afforded us two advantages. First, it allowed us to compare symptoms of autism to multisensory processing without the participants knowing that we were directly comparing these two factors; since the participants completed nearly 20 assessments (see "Appendix") in their first visit to the laboratory, there was no means for them to know which specific measures (if any) were of interest on their subsequent visits. Second, this design provided additional assessments that could be used to ensure that any found relationship between autism and multisensory processing is related to autism *per* se and not mediated by another factor (e.g., video game experience; Donohue et al. 2010). Some of the participants made additional visits to the laboratory to take part in other experiments such as the visual–visual temporal-order judgment task, described below.

Stimuli and task

The current experiment is an exact replication of the central presentation simultaneity judgment task of Donohue et al. (2010). Auditory and visual stimuli were presented using Presentation (Neurobehavioral Systems) at thirteen stimulus onset asynchronies (SOAs in ms: −300, −250, −200, −150, −100, −50, 0, 50, 100, 150, 200, 250, 300) where negative SOAs represent the auditory stimulus appearing first and positive SOAs represent the visual stimulus appearing first, and 0 represents physical simultaneity. Note that a typical window of integration ranges from −150 to 150 ms so, subjectively, approximately half of the SOAs should be perceived as simultaneous presentations even though only one is objectively simultaneous. The auditory and visual stimuli were both presented for 33 ms. The auditory stimulus was a 1,200 Hz tone, 5 ms rise-and-fall time, the volume of which was titrated to be 60 dB above each participant's hearing threshold, and it was presented centrally through two speakers on either side of the monitor. The visual stimulus consisted of a black-and-white square checkerboard pattern (5° × 5°, centered 3.4° below fixation, with participants seated ~57 cm from the monitor; see Fig. 1). On each trial, the participants were to judge the temporal simultaneity of the auditory and visual stimuli. They made a self-paced key-press response to report whether the presentation was 'simultaneous' or 'not simultaneous.' After a practice block of 26 trials, they completed 312 test trials (24 trials for each of the 13 SOAs) with a different random trial order presented to each participant.

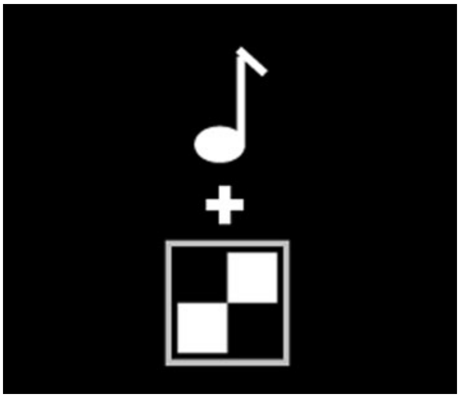

Fig. 1 Simultaneity Judgment Task. Participants attended to auditory tones and visual checkerboards, both presented centrally, to determine if the auditory and visual stimuli occurred simultaneously or were offset in time

Data fitting

The primary measure of interest was the proportion of trials reported as 'simultaneous' at each SOA. These data were fit for each participant to a Gaussian function using a nonlinear least-squares fit using MATLAB (MATLAB Optimization Toolbox, Mathworks, Natick, MA, USA), and from these fits, we obtained the mean and standard deviation for each participant's function (see Donohue et al. 2010; Zampini et al. 2005). The mean corresponds to the point of subjective simultaneity (PSS), or the SOA at which participants are most likely to judge the audio–visual pair as simultaneous. An ideal participant would have a mean, or PSS, at the 0 SOA. A participant with a bias to perceive auditory information before visual would have a negative mean, and a participant with a visual first bias would have a positive mean. Data from 13 participants were excluded from the analyses because their calculated PSS exceeded the SOAs tested, suggesting that they were unable to (or refused to) follow the task instructions and perform the task correctly (Donohue et al. 2010). The standard deviation corresponds to the spread of the participants' distribution. A broader spread (i.e., higher standard deviation) represents poorer precision as is corresponds to participants judging more of the temporally offset stimuli as occurring simultaneously.

Results

Autism spectrum quotient questionnaire (ASQ)

The individual scores on the ASQ ranged from 2 to 33 with a mean of 18.39 (SD = 5.72). The higher the score, the more autistic symptoms an individual reported.

Simultaneity judgment task

The points of subjective simultaneity (PSS) ranged from −64.28 to 128.86 ms, with a mean of 41.27 ms (SD = 44.24 ms). Negative values indicate that the participant was more likely to perceive the stimuli as simultaneous when the auditory stimulus came before the visual, and positive values indicate that the stimuli were perceived as simultaneous when the auditory stimulus came after the visual. The standard deviations for each participant (i.e., the spread of their judgment curve) ranged from 56.00 to 328 ms, with a mean of 174.61 ms (SD = 55.82 ms). For the participants tested here, these data suggest (as observed in Donohue et al. 2010) that participants are more likely to perceive audio–visual stimuli as occurring simultaneously when the visual stimulus comes before the auditory stimulus. Further, there is a broad temporal window over which participants will temporally link multisensory information.

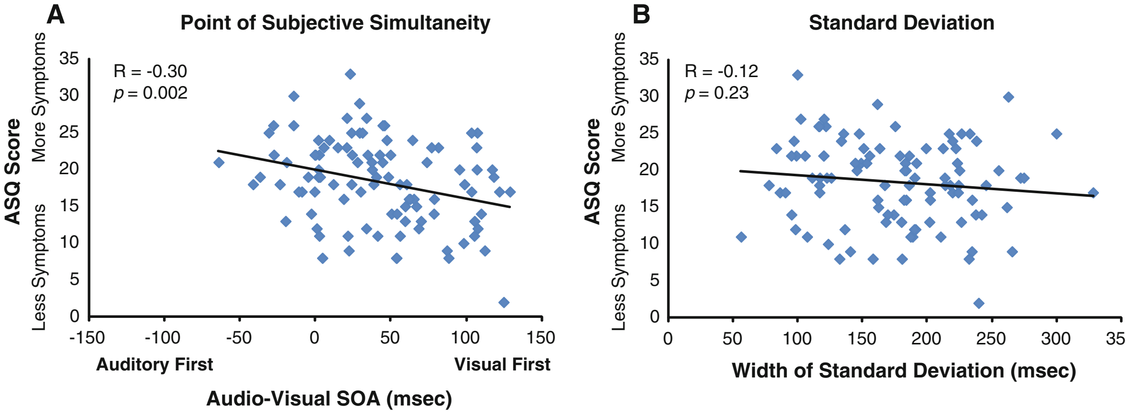

Fig. 2 **a** Significant correlation between the multisensory task PSS and the autism spectrum questionnaire (ASQ), wherein the PSS shifted to the left (toward an auditory-first bias) as ASQ scores increased. **b** Correlation between the width of the standard deviation in ms obtained from the fit multisensory data, and the ASQ was not significant, suggesting that the shape of the temporal window of integration, while variable across the population, did not relate to the ASQ

Multisensory processing and autistic symptoms

The PSS for the multisensory simultaneity judgments significantly correlated with the scores on the ASQ (see Fig. 2; $R = -0.30$, $p = 0.002$[2]). Specifically, as participants' scores on the ASQ increased (signifying more self-reported symptoms of autism), their PSS shifted leftward (representing a bias to report auditory-first presentations as simultaneous). The standard deviation was not significantly correlated with the ASQ across participants ($R = -0.12$, $p = 0.23$).

The ASQ contains five subscales, and to further examine the relationship between symptoms of autism and multisensory processing, we correlated each subscale with the PSS and the standard deviation. Social skill ($R = -0.29$, $p = 0.003$), attention switching ($R = -0.22$, $p = 0.03$), communication ($R = -0.26$, $p = 0.01$), and imagination ($R = -0.23$, $p = 0.02$) were all significantly correlated with the PSS, while attention to detail was not significantly correlate with the PSS ($R = 0.11$, $p = 0.29$). When all of the subscales were entered into a multiple regression to determine which of these subscales best predicted the PSS, only attention switching emerged as a significant predictor (Beta $= -0.21$, $t(100) = -2.21$, $p = 0.03$). The standard deviation did not significantly correlate with any of the subscales (all p's > 0.1), and none of the subscales emerged as significant predictors of standard deviation when entered into a multiple regression analysis (all p's > 0.2).

Additional analyses

In the primary analyses, we demonstrated that the PSS in a simultaneity judgment task significantly correlated with ASQ scores. This is an intriguing result, but before discussing the implications, it is important to first address possible alternative accounts. Below we address two concerns—one for the multisensory aspect of the results and one for the autism aspect of the results. First, one could argue that the found relationship may be related to temporal processing in general and not to multisensory processing *per se*. To address this concern, we present data from participants in an additional visual–visual temporal-order judgment task wherein there was no correlation between task performance and the ASQ. Second, it is important to establish the specificity of this found effect to autism symptoms *per se*. To address this, we present data from multiple regression models that demonstrate that while video game playing and symptoms of ADHD both correlate with the PSS, neither accounts for the found relationship between the PSS and the ASQ.

Confirming the multisensory aspect of the found link between autism and multisensory processing

It is possible that the primary results presented above, that the PSS in a multisensory simultaneity judgment task correlates with symptoms of autism, could represent hindered temporal processing for individuals with higher symptoms of autism, and the multisensory aspect is incidental. That is, does the found relationship speak to the nature of temporal processing or to the nature of *multisensory* temporal processing? Previous evidence strongly suggests that autism is linked to abnormal multisensory processing (Kwakye et al. 2011) so this concern is not

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[2] No data were removed from this correlation as outliers since data were already removed from participants who had a PSS outside the range of SOAs tested (i.e., those who were unable/refused to do the task). As seen in Fig. 2a, one participant scored low on the ASQ. However, with this data point removed, the correlation is still highly significant ($R = -0.26$, $p = 0.008$).

overly strong. Nevertheless, here, we present additional data that is consistent with a multisensory interpretation. Specifically, we compare performance from a visual–visual temporal-order judgment task to symptoms of autism; if the primary results are specific to multisensory processing, no relationship should arise from this visual–visual task.

Eighty-two participants (mean age = 20.7 years, SD = 6.22; 54 female, 23 of whom were also participants in our multisensory simultaneity judgment task) completed a visual–visual temporal-order judgment task and also completed the ASQ questionnaire (the questionnaire was completed as part of the same process as described above). In this task, two visual stimuli (red boxes, 2.7 × 2.7°, 1.85° below fixation) were presented to the left side and to the right side of the screen, respectively, in two arrangements. In the near condition, the boxes were 8.2° apart (in the horizontal direction), and in the far condition, the boxes were 16.4° apart horizontally, with the fixation cross always being central to the two boxes. These boxes were presented at 13 SOAs (−96, −60, −48, −36, −24, −12, 0, 12, 24, 36, 48, 60, 96) where negative SOAs indicate the left visual stimulus came first and positive SOAs indicate the right stimulus came first. Participants were asked to report whether the left or right stimulus appeared first via button-press, and the proportion of each type of response was obtained across the SOAs.

The primary analyses reported above focused on biases in the temporal perception of auditory and visual stimuli. A visual–visual judgment task does not present meaningful temporal biases, but rather provides metrics of absolute accuracy. Accuracy was assessed in two separate analyses for this task, conducted separately for the near and far conditions. Accuracy was calculated as the percentage of trials in which the left square was reported as appearing first (ideal performance would be a square function with 100 % for the negative SOAs, chance performance at the 0 SOA, and 0 % for the positive SOAs). First, the data from the middle SOAs (−12, 0, 12) were fit to a linear function; more accurate participants will have a steep, negative slope since an ideal observer would report the left square appearing first 100 % of the time at the −12 SOA, 50 % at the 0 SOA (chance), and 0 % at the +12 SOA (this would be a slope value of −4.2). The values of the slopes (Near: $M = -0.69$, $SD = 0.77$; Far: $M = -0.42$, $SD = 0.75$) were correlated with the ASQ scores ($M = 16.80$, $SD = 6.40$) which produced no significant relationship[3] (Near: $R = -0.19$, $p = 0.09$; Far: $R = -0.06$, $p = 0.62$). Second, accuracy was collapsed across the first five SOAs (−96, −60, −48, −36, −24) and the last five SOAs (24, 36, 48, 60, 96); ideal performance would be a response of ‘left first’ 100 % of the time at the first five SOAs and 0 % of the time at the last five SOAs. Proportion correct data were averaged for the first five SOAs and the last five SOAs (transformed for the last five so that the 0 % would be 100 %). These data (Near: $M = 90$ %, SD = 7 %, Far: $M = 82$ %, SD = 8 %) were correlated with the ASQ data. Again, no significant relationship between ASQ and accuracy was observed (Near: $R = -0.08$, $p = 0.50$; Far: $R = -0.17$, $p = 0.13$).

Confirming the autism aspect of the found link between autism and multisensory processing

How do we know that the found relationship is driven by symptoms of autism and not some other individual difference measure? By the design of the study, participants completed not only the ASQ survey, but also a wide array of other measures. Our targeted focus here was on symptoms of autism, but this design allows us to determine if other factors contributed to the relationship.

In our previous work, we had observed a significant relationship between video game expertise and multisensory PSS and standard deviation (Donohue et al. 2010). This, therefore, was an important factor to rule out as it could possibly account for a portion of the variance between the PSS and the ASQ. Likewise, we felt it was important to account for any possible contribution from symptoms of ADHD. ADHD has been linked to broad attentional and perceptual deficits and has often been found to be present in individuals with autism (e.g., Leyfer et al. 2006). Our collection of questionnaires, included a laboratory-created assessment of video game playing habits and experiences (see Clark et al. 2011; Donohue et al. 2010) and the Jasper/Goldberg Adult ADHD Questionnaire (Jasper and Goldberg 1993). We conducted a regression analysis including these measures to directly rule out contributions of action video game experiences and symptoms of ADHD.[4]

Point of subjective simultaneity (PSS)

To determine if variability in the ASQ continued to predict performance on the multisensory simultaneity judgment task when accounting for video game expertise and ADHD symptoms, we used a multiple regression model technique. We computed three models (see Table 1): Model 1: action video game expertise, Model 2: video game expertise and ADHD scores, and Model 3: video game expertise, ADHD,

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[3] The alpha level necessary to reach significance here is 0.025 via Bonferroni correction for multiple comparisons since two different analyses are being run on both the near and the far data.

[4] There were several other assessments obtained from our participants in their first visit; however, we are only analyzing (and reporting here) the tests conducted based on a priori predictions about the relationships between video game play, ADHD, and multisensory processing.

Table 1 Multiple regression models to examine the relationship between the multisensory PSS and video game playing, ADHD, and ASQ scores

Model	Adjusted R^2	Standard error of the estimate	F change	Sig. change
1	0.032	43.53	4.28	0.041
2	0.079	42.46	6.04	0.016
3	0.111	41.71	4.58	0.035

Model 1: Constant and video game playing expertise. Model 2: Constant, video game playing expertise, and ADHD scores. Model 3: Constant, video game playing expertise, ADHD scores, and ASQ scores. Model 3 significantly improved upon the first two, highlighting that, even when taking these other factors into account, the relationship between the multisensory PSS and ASQ scores still held

and ASQ scores. The critical question is whether Model 3 accounts for any of the variability in performance above and beyond Models 1 and 2. As predicted, all three factors (video game experience, ADHD, and autism) significantly contributed to performance. Importantly though, when taking into consideration both video game expertise and ADHD scores (Models 1 and 2), participants' scores on the ASQ still significantly predicted their PSS for the multisensory simultaneity judgment task (Model 3; beta $= -0.22$, $t(100) = 2.14$, $p = 0.035$).

Standard deviation

While there was no significant relationship found between the ASQ and the standard deviation in the current experiment, our previous work did find a relationship between video game playing experiences and the standard deviation (Donohue et al. 2010). For completeness, we used the same model logic described above to examine how video game experience, ADHD, and autism related to variability in the standard deviation. The only significant predictor was video game playing expertise, which held even when taking into consideration the ADHD and ASQ scores (beta $= -0.271$, $t(100) = 2.52$, $p = 0.013$). Collectively, these analyses replicate of our previous results (Donohue et al. 2010) for both the PSS and standard deviation and video game playing expertise, showing a shifted PSS toward a bias of reporting auditory-first stimuli as simultaneous and a narrower temporal window of integration for video game players.

Discussion

Autism is a complicated disorder that lacks uniformity. Diagnosed individuals can be high-functioning with minimal or highly focused symptoms, can be low-functioning with severe and debilitating symptoms, or can be anywhere in between. Moreover, non-diagnosed individuals from the general population can suffer from a wide range of autistic symptoms. This natural variation has made autism a difficult disorder to classify and understand, but it has also made it a highly fruitful research realm. As more and more research is done in relationship to autism, we are able to learn more about the disorder itself and about general cognitive and social processing. The current study took a non-traditional approach to examining relationships between cognition and clinical disorders; rather than testing group differences between clinical and non-clinical populations, here, the focus was on a continuum of symptoms within a 'healthy' population. This approach proved fruitful as it was found that the temporal aspects of multisensory processing correlated with symptoms of autism.

The nature of the current experimental design provided a means to rule out potential confounds. First, it was theoretically possible that the relationship between temporal multisensory processing and symptoms of autism was not unique to multisensory processing, but rather was an instantiation of a broader link between temporal processing in general and autism. This alternative account is diminished by the fact that a visual–visual temporal-order judgment task (i.e., a non-multisensory measure of temporal processing) did not related to autism. This account is further diminished by recent work that found that, compared to typically developing children, children with autism had a broader temporal window of integration for multisensory stimuli but not for visual stimuli (Kwakye et al. 2011). Interestingly, Kwakye et al. (2011) also found altered temporal processing for auditory stimuli in children with autism as compared to typically developing children. Indeed, it is possible that the results reported here of a shift in multisensory processing abilities could be the result of altered auditory temporal processing. Without an auditory task to rule out this possibility, our data can only speak to the fact that these differences ramify as differences in multisensory processing; regardless of the origin, it is the temporal binding of multisensory stimuli that is affected with increasing ASQ scores. And, importantly, it is this binding that allows one to accurately integrate together the multisensory objects in the surrounding environment. Moreover, the visual–visual temporal-order judgment task does suggest that the results here are not merely due to global differences in the temporal processing of stimuli.

Second, it was possible that the current results may have manifested from another factor (such as video game playing), rather than from a relationship with autism *per se*. Video game playing experience represented a legitimate alternative, given it has previously been linked to multisensory processing on the task employed here (Donohue et al. 2010). Likewise, ADHD served as another possible alternative factor given that ADHD is often found to be comorbid with autism. While both video game playing experience and ADHD symptoms were significantly correlated with multisensory processing, autism still significantly correlated with multisensory processing when both of these factors were taken into account.

The process of eliminating alternative accounts to our primary result that multisensory processing is related to symptoms of autism produced additional findings of note. First, the current study replicated our previous work demonstrating a relationship between multisensory processing and video game playing experiences (Donohue et al. 2010). Moreover, this replication comes from a broader population (e.g., our earlier study focused exclusively on male participants). Second, we demonstrated that multisensory processing correlated with symptoms of ADHD. The individuals in our sample with higher symptoms of ADHD likely had trouble sustaining focus during the task. As such, the particular trials in which the stimulus order would have provided the most attentional capture (i.e., those with the auditory stimuli coming first) would have likely been the ones to which the participants with the higher ADHD scores would have paid the most attention, and therefore likely integrated the most if the stimuli were occurring close together in time. Regardless of the explanation, further work should be done to examine the links between ADHD and multisensory temporal processing.

Having addressed alternative explanations for our primary result, additional questions then arose. Specifically, it is worth considering why participants with higher levels of autism symptoms would be more likely to perceive the presentation as simultaneous when the auditory stimulus came first. On average, the current participant population had a point of subjective simultaneity (PSS) that represented perceiving simultaneity when the visual stimulus came first. This is in line with past findings as well (e.g., Donohue et al. 2010; van Wassenhove et al. 2007; Zampini et al. 2005), and an ecologically valid bias; light travels faster than sound, and so sources from the same (distant) event would reach the sensory organs at different times, with the visual arriving first. While the current correlational data cannot speak to a causal relationship, it would appear that with increasing symptoms of autism, the PSS shifts toward a point that is less ecologically valid. When considering why this might be, some potential evidence from both research (Dahlgren and Gillberg 1989; Tomchek and Dunn 2007) and anecdotes (Cesaroni and Garber 1991) point to a greater sensitivity for auditory stimuli in individuals with autism. It is possible therefore that the auditory stimuli received 'priority' within these individuals and therefore were more salient (potentially capturing attention) and were processed for a longer period of time. This could indeed result in the pattern of findings observed here, and further studies, perhaps using electrophysiological measures could confirm this.

Further, it is worth noting that the present study found a relationship between symptoms of autism and the PSS but not the standard deviation, while Kwakye et al. (2011) found that children with autism had a broadened temporal window of integration (an effect that would manifest in the standard deviation). Kwakye et al. (2011) tested children with and without autism and the current study tested adults from the general population, and it is possible that these experimental differences may underlie the differences in results. It is also possible that the broadening of the temporal window does not occur to a measurable extent within the general population. Likewise, it is unclear if adults with autism would also have a broadened temporal window of integration, or if this would change over development.

Finally, the assessment of which specific subscales within the ASQ correlated with multisensory temporal processing provided further insight into which particular cognitive functions within autism may be directly related to multisensory processing. We found that communication, imagination, attention switching, and social skill all correlated with the PSS, while attention to detail did not. Further, when analyzed with a multiple regression, attention switching was the only subscale that predicted the PSS. It is likely that those participants who had deficits in the ability to switch attention may have had an altered PSS due to perseveration on a specific modality. As multisensory processing is also highly important for cognitive and social processes such as 'communication' and 'social skill,' it is not surprising that these were correlated with the PSS. Future work could build off of the current findings with a healthy adult population to tease apart the specific facets of autism that are the most directly related to multisensory processing at the clinical level.

An overarching goal of the current project was to simultaneously inform both the study of autism and the study of multisensory processing by exploring them in tandem. For the field of autism research, the current results demonstrate that meaningful findings can come from studying a range of autistic symptoms in a general adult population. This is informative as it suggests cognitive deficits linked to autism can be explored without requiring clinical populations. More specific to the current multisensory focus, these results supports recent findings (Megnin et al. 2012) to further strengthen the curious finding that those who suffer from autism may have difficulty with perceptual binding. For the study of multisensory processing, the current study demonstrated widespread individual differences in temporal processing abilities across a young adult population. This highlights that individual variability should be taken into consideration when studying the binding of multisensory stimuli.

Further, not only do the current results reveal variability across individuals, but they also provide specific predictors of performance; autism, video game playing, and ADHD all correlated with multisensory processing abilities.

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Appendix for Donohue, Darling, and Mitroff

The Duke Visual Cognition Laboratory administers a ‘battery’ of individual differences assessments as part of an experimental protocol to understand how cognitive abilities vary across participants. Below we provide the self-report questionnaires that were administered at the time of testing for this study’s participants.

Self-report questionnaires examined for the current study

- Autism Spectrum Quotient (ASQ; Baron-Cohen et al. 2001)
- Attention deficit hyperactivity disorder (ADHD; Jasper and Goldberg 1993)
- Video game playing questionnaire (*designed in laboratory*)

Questionnaires administered to participants but not examined for the current study

- Race/Ethnicity
- Society Works Best (Smith et al. 2011)
- Language Experience and Proficiency Questionnaire (LEAPQ; Marian et al. 2007)
- General pastimes questionnaire (*designed in laboratory*)
- Maximization scale (Schwartz et al. 2002)
- Eating Attitudes Test (EAT; Garner and Garfinkel 1979)
- Media Multitasking questionnaire (MMI; Ophir et al. 2009), 101 participants
- Wilson and Patterson (1968)
- Edinburgh Handedness Inventory (EHI; Oldfield 1971)
- Positive and Negative Affect Schedule (PANAS; Watson et al. 1988)
- NEO Personality Inventory (NEO-PI-R; Costa and McCrae 1992)
- Religious Beliefs (*designed in laboratory*)
- Trait Anxiety (Taken from State-Trait Anxiety Inventory; Spielberger et al. 1983)
- Regulatory Focus (Higgins et al. 2001)

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