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Visual Processing Across Space and Time in Children with Autism Spectrum Disorder

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Abstract

Individuals with autism spectrum disorder (ASD) demonstrate enhanced perceptual abilities relative to typically developing (TD) peers, as evidenced by better detection and identification of visual targets. This enhanced ability to discriminate features has been replicated across spatial and temporal displays. Research also suggests that visual perceptual abilities are correlated with the severity of core autism symptoms in this population, with the exception of atypical sensory behaviors, including sensory seeking and aversion, in which the relationship has been understudied and remains poorly understood. The current study introduces a novel visual search task to assess identification accuracy of feature-based visual targets that concurrently manipulates the temporal and spatial presentation of targets and distractors among children with and without ASD. In the task, target and distractor stimuli were simultaneously presented over visual space on a computer screen, with the peripheral distance of target stimuli from the center of the screen manipulated across trials (close, medium, and far), and the presentation rate manipulated across blocks (39, 117, and 195ms). Results revealed a perceptual advantage in children with ASD when targets were presented close to the center of the display at a presentation rate of 195ms, but not at other rate/distance combinations. Several significant correlations were found between perceptual accuracy and core ASD traits, including atypical visual sensory behaviors. Conclusions are limited by the smaller than expected sample size (due to COVID-19 and abrupt discontinuation of data collection), and data collection will resume when possible to clarify findings. Nonetheless, results provide important insights into the nature of perceptual processing, both in individuals with ASD and TD individuals, in the context of simultaneous spatial and temporal constraints. Clinical implications, limitations, and future directions are discussed.

Keywords: Autism spectrum disorder, visual perception, sensory processing

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Table of Contents

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Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by impairments in social communication and the presence of restricted, repetitive behaviors and patterns of interest (American Psychiatric Association, 2013). Although the cause of ASD is unknown, prevalence rates have been increasing over the past several decades (Neggers, 2014), with the most current estimates reporting a prevalence of 1 in 54 children diagnosed with ASD with a higher rate in males than in females (4:1; CDC, 2020). Accordingly, it is clear that more and more children with ASD will require specific supports in their home and educational settings, and thus gaining a better understanding of the unique abilities of these children will be vital in developing appropriate interventions and accommodations to support effective learning and skill acquisition.

Although the core features of ASD include impairments in social communication and the presence of restricted, repetitive behaviors, many individuals on the spectrum also exhibit sensory differences compared to their typically developing (TD) peers. In fact, hyper- or hyposensitivity to sensory input has recently been added as a common, though not required, symptom of ASD in the latest Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5; American Psychiatric Association, 2013). Sensory processing differences have been observed in autism since its conception (Kanner, 1943) and today, are often measured clinically through parent questionnaires reflecting *observable* behavioral reactions including sensation seeking behaviors (e.g., fascination and inspection of flickering lights or spinning objects), and sensation aversion (e.g., adverse reactions to bright lights, loud noises, and particular smells, textures, or temperatures; Ben-Sasson et al., 2009; Hazen, Stornelli, O'Rourke, Koesterer, & McDougle, 2014; Wiggins, Robins, Bakeman, & Adamson, 2009).

Relatedly, researchers have also investigated perceptual processing differences in ASD, or how those with ASD report their experience of the world across sensory modalities. Although sensory processing and perceptual processing are inherently linked and difficult to disentangle from one another (Goldberg, Perfetti, & Schneider, 2006; Goldstein & Brockmole, 2016), the characterization of sensory behaviors (Ayres & Tickle, 1980; Ornitz, 1974) and perceptual abilities (Happé & Frith, 2006; Mottron, Dawson, Soulières, Hubert, & Burack, 2006) have largely been studied and conceptualized separately in the field of autism research. Although these constructs have often been used interchangeably, there is currently a poor understanding of exactly how and whether they are linked in ASD (Mottron, 2019), which will be addressed further in the current study. While research has documented *perceptual* processing differences in ASD across visual, auditory, and tactile modalities, as well as multisensory integration (Marco, Barett, Hinkley, & Hill, 2012; O'Connor, 2012; O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001; Plaisted, O'Riordan, & Baron-Cohen, 1998; Tavassoli et al., 2016), perhaps the most well-studied and robust area of literature is within the visual domain.

Visual perceptual abilities, henceforth referred to as visual processing abilities, are vital for success in our environmental contexts. For example, imagine you are a student walking into a classroom. You may encounter a maze of desks and chairs, art projects and posters lining the walls, books and supplies scattered along various shelves, other students scurrying about the room, and instructions written on the board. Each moment you rely on your visual processing abilities to successfully navigate the room, read the instructions, locate necessary materials, and accurately complete tasks. Whether it be in a classroom or elsewhere, our environments contain visual information that we must sense, perceive, filter, and selectively attend to in order to learn and make decisions that will lead to successful functioning. Gaining a better understanding of visual processing differences in ASD is vital to the development of interventions that can meaningfully target learning and behavioral functioning to improve outcomes.

Although visual processing is a broad construct, it can be broken down into more detailed and specific abilities, each of which is likely processed and controlled by different areas of the visual system and visual cortex. For example, abilities such as binding features to objects to facilitate object recognition (Cortese, Bernstein, & Alain, 1999; A. Treisman, 1996), detecting salient and meaningful objects among irrelevant objects in varying spatial and temporal arrangements (Treisman, 1982; Treisman & Gelade, 1980; Wolfe, 1994), detecting motion (Alais, Blake, & Lee, 1998), and so on, each occur through distinct neurological pathways, while collectively contributing to our ability to successfully function within our environmental contexts. Of particular relevance to the current study is the ability to detect and identify visual features (e.g., color); an ability that has been characterized over the spatial domain (i.e., when objects are presented in an array across visual space) and temporal domain (i.e., when objects are presented over time) using a variety of behavioral tasks that have been extensively developed and studied by vision researchers (Chun & Potter, 1995; Treisman, 1982; Treisman & Gelade, 1980; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). In reality, we process visual information as it unfolds over both space and time, often simultaneously, making it important to understand both commonalities and differences in these domains that may contribute to our understanding of visual processing differences in ASD. The current study borrows components from both spatial and temporal visual processing experimental paradigms, details of which are discussed below.

Visual Processing Over Space and Time

The most relevant theories of visual processing to the current study are ones that make claims about the processing of feature-based stimuli over space, as participants were required to search for feature-based visual targets across spatial arrays. While debates and opinions precede the formal theories of how visual features are processed, Treisman and Gelade (1980) formalized Feature Integration Theory, which posits that two separate stages are involved in processing the spatial visual world, and emphasizes the features of objects as playing a key role in the first, pre-attentive "parallel" stage. Based on physiological evidence suggesting that different object features such as color, size, shape, orientation, and movement are each processed by specialized populations of receptors in the retina, Treisman and Gelade (1980) proposed that visual features of several objects in the environment, over a large spatial area, are processed in "parallel" (i.e., simultaneously) to aide filtering efficiency and allow for detection of relevant and meaningful stimuli. For example, if you are looking for a book on a bookshelf that is short and green, theoretically you are able to process the colors and sizes of many books on the shelf simultaneously via parallel processing. Unless there are many short, green books on your shelf, you are likely to spot the book you're looking for quite efficiently. The "pop-out" effect is a term that has often been used to describe these situations in which a salient, easily discriminable stimulus feature allows for efficient, parallel processing to occur in visual search (Dehaene, 1989; Wang, Cavanagh, & Green, 1994) and has been demonstrated across features of color, shape, size, curvature, and orientation (Dehaene, 1989).

However, let's consider the case in which there *are* many short, green books on your shelf. Treisman and Gelade (1980) would argue that this situation requires a second "serial" stage of attentive processing, in which items with similar features are more closely observed over much narrower spatial areas, until the correct book is located. So, instead of surveying the entire bookshelf, perhaps you would need to view a group of three or four short, green books and search for details such as the author's name that you're looking for. This serial processing of information is less efficient than parallel processing but is required when the target shares some stimulus features with distractors (i.e., a conjunction of features). A series of experiments (Treisman, 1982; Treisman & Gormican, 1988; Treisman & Gelade, 1980) provided support for the notion of distinct parallel and serial processes, reporting that across several manipulations and feature-based stimulus characteristics, search time was significantly longer on conjunctive search tasks, when targets shared features with distractors, compared to when they had a unique feature.

Building off of the work of Treisman and Gelade (1980), Wolfe (1994) introduced the Guided Search Model, which was motivated by research findings that somewhat opposed Treisman's Feature Integration Theory, demonstrating that parallel processing was sometimes possible when targets and distractors shared some features (or at least yielded reaction times similar to parallel search), depending on variables like stimulus salience (Duncan & Humphreys, 1989; Treisman & Sato, 1990; Wolfe, Cave, & Franzel, 1989) and density or crowding of items in the display (Cohen & Ivry, 1991). Wolfe posited that earlier, pre-attentive (i.e., parallel) processes serve to "guide" and deploy attention to a more focal spatial location in which limited-capacity (i.e., serial) processes can occur. In his model, when target and distractor features are less discriminable, these limited-capacity processes are often deployed multiple times to different spatial locations before a target can be detected, resulting in longer search times. The theories and models introduced Treisman and Gelade (1980) and Wolfe (1994) form the basis for the most current conceptualization and understanding of the visual processing of features over space and converge on the finding that meaningful objects in space that possess distinct and easily discriminable features from surrounding objects (which will be utilized in the current study) are detected and processed most efficiently.

Although much of the existing literature on visual processing involves spatial search tasks (which can often include both spatial and temporal components), some researchers have attempted to isolate the temporal domain of visual processing in order to better understand if similar phenomena occur when spatial search is not required. One method that has been used to characterize visual processing across time is called rapid serial visual presentation (RSVP; Chun & Potter, 1995). This method isolates the temporal aspect of visual processing by presenting all stimuli in a fixed spatial location over time. Like spatial search tasks, these temporal tasks have utilized both feature and conjunctive search to assess detection accuracy at varying presentation rates across time, and have also found that targets are more accurately detected when their visual features are more easily discriminable from distractors (Chun & Potter, 1995; Cortese et al., 1999).

Visual Processing in ASD

Several experiments have investigated the visual processing abilities of individuals with ASD relative to TD individuals, primarily through the use of spatial and temporal search tasks similar to the ones just described, and have documented a variety of differences in the spatial, temporal, and peripheral domains.

Spatial Visual Processing in ASD

Studies investigating visual processing over space in ASD have found that individuals on the spectrum demonstrate enhanced performance on both featural and conjunctive visual search tasks in which various stimuli were scattered across a screen, either randomly or in predetermined locations. Plaisted et al. (1998) and O'Riordan et al. (2001) investigated the performance of children with ASD with an average age of 8 years and TD peers matched by age and IQ scores on both feature-based and conjunctive visual search tasks. Results revealed that children with ASD responded significantly faster (O'Riordan et al., 2001; Plaisted et al., 1998) and more accurately (Cohen's $d = 0.51$, Plaisted et al., 1998) than TD children on the conjunctive search task in which participants were asked to report the red X among green X and red T distractors, as well as on two difficult feature-based search tasks in which the target and distractors were either vertical or tilted lines (O'Riordan et al., 2001). These findings were later replicated in adults with ASD using the exact same conjunctive and feature-based visual search tasks (O'Riordan, 2004).

O'Riordan (2004) also aimed to expand upon the notion of enhanced feature-based visual processing in ASD by investigating item discrimination ability. In two additional experiments, the author manipulated the similarity of target and distractor items; in the easier task, participants were asked to detect a red X amongst green X and red C distractors, while in the harder task, individuals were required to spot the red F amongst pink F and red E distractors (this task being harder because red and pink are less easily discriminable). Display sizes were manipulated such that there were 5, 15, or 25 distractors on any given trial. Individuals with ASD demonstrated significantly faster reaction times on trials with 25 distractors compared to TD peers across the two experiments and were significantly more accurate at detecting targets on the more difficult task, suggesting that when item discriminability is made more difficult, adults with ASD show superior performance relative to TD adults. These findings not only provide support for the idea that individuals with ASD exhibit faster and more accurate processing of visual features, but also that this may stem from a superior ability to *discriminate* more similar features from one another.

Although the findings of O'Riordan (2004) suggest enhanced discrimination abilities in individuals with ASD, it remained somewhat unclear whether this was related to more efficient visual search in the context of larger set sizes (i.e., more distractors), or superior perceptual processing of stimulus features once the target was located. Joseph, Keehn, Connolly, Wolfe and Horowitz (2009) used two visual search tasks to investigate this question in school-aged children with ASD, matched to TD children by age and nonverbal IQ. In both a static visual search task and a dynamic task (in which targets and distractors changed location on the on the screen every 500ms), the black target letter T was presented among black distractor letter L's of varying set size (15, 20, or 25).

In both tasks, children with ASD demonstrated faster reaction times compared to TD children. Joseph et al. (2009) also looked at a reaction time by set size function and partitioned this into slope and intercept values for each participant, which has been done in this type of task previously (Sternberg, 1966). In this way, the slope represents the reaction time cost of each additional distractor item and is thought to measure efficiency related to visual search (with shallower slopes being more efficient). On the other hand, the intercept is thought to represent the reaction time that would be observed if search was not required. In other words, the intercept can be thought of as a measure of the efficiency of non-search related processes such as early pre-attentive processing of the perceptual features of stimuli. Results revealed that the reaction time by set size slopes did not differ significantly between the two groups, but that the intercepts were significantly lower for those with ASD compared to TD children. Analysis of eye tracking data also revealed no differences between the two groups in terms of the number and spatial distribution of eye fixations. The authors concluded that the enhanced ability of individuals with ASD to detect feature-based targets in visual search tasks, both in their experiment as well as others, was likely due to superior ability in the perception of object features rather than superior search efficiency.

This interpretation seems consistent with a common theme observed across all experimental tasks that have demonstrated enhanced visual processing across space in individuals with ASD (Joseph et al., 2009; O'Riordan, 2004; O'Riordan et al., 2001; Plaisted et al., 1998), which is that they all utilized target and distractor stimuli that differed by visual features (e.g., color, shape). As such, it seems quite possible that enhanced perception of visual features may underlie the visual search advantages observed in this population.

Temporal Visual Processing in ASD

The majority of experimental research investigating feature-based visual processing abilities in individuals with ASD has focused on the spatial domain, while far fewer studies have examined the temporal limits of these skills. However, given that perceptual processing seems to be the enhanced ability in ASD rather than search efficiency (Joseph et al., 2009), testing the temporal limits of this efficiency while excluding the need to search for stimuli in a spatial array would be useful. Hagmann et al. (2016) attempted to examine this by utilizing a rapid serial visual presentation (RSVP) task which isolates the temporal aspect of visual processing by presenting stimuli one after another in a fixed spatial location (Chun & Potter, 1995). In the Color Task of this experiment, 16 letters were presented in the center of a computer screen at rates of 50, 83.3, and 116.7ms per item and participants were asked to detect the purple target letter among a stream of black distractor letters. Children with ASD between the ages of 7 and 17 were found to be significantly more accurate at detecting the purple letter at the fastest presentation rate (50ms) compared to TD children matched by age and IQ, with a medium effect size (Cohen's $d = 0.51$). In fact, children with ASD showed similar levels of accuracy at this rate as TD adults between the ages of 18 to 25 years old. No differences were observed between those with ASD and the child and adult TD groups at slower presentation rates.

Kopec et al. (*in press*) aimed to replicate and extend the findings of Hagmann et al. (2016) using an identical experimental paradigm, but by adjusting the presentation rates to surround the 50ms rate that was found to be significant between groups (i.e., 13ms, 26ms, 39ms, 65ms, and 91ms). Results revealed that children with ASD between the ages of 7 and 17 years old demonstrated numerically higher levels of target accuracy than TD peers across all presentation rates, with statistically higher accuracy at the 39ms and 65ms presentation rates, with medium effect sizes (Cohen's $d = 0.63$ for 39ms and 0.55 for 65ms). Interestingly, parent-reported autism-related traits predicted more accurate performance at the two fastest presentation rates (i.e., 13ms and 26ms) across both groups, despite a lack of significant group differences. Results of Kopec et al. (*in press*) and Hagmann et al. (2016) suggest that individuals with ASD demonstrate enhanced perception of visual features in the temporal domain relative to TD peers of the same age and cognitive ability, but that these enhancements may be confined to a specific temporal window.

Notably, the current study is largely an adaptation of the experimental paradigm used in the Hagmann et al. (2016) and Kopec et al. (*in press*) studies which was developed for use in the Center for Autism Research and Electrophysiology (CARE) lab at Syracuse University. An important goal of the current study was to continue expanding upon the overall findings of various experiments in the lab. In addition to the findings of Hagmann et al. (2016) and Kopec et al. (*in press*), other studies in the lab have found that individuals with autism show enhanced perceptual accuracy on a feature-based temporal search task involving targets with conjunctive features (i.e., shared with some distractors; Kopec et al., 2018) as well as on a dual target task, when two purple letters were presented in the temporal stream (Kaplan et al., 2018). While the overarching goal of these experiments has been to characterize visual perceptual abilities in the temporal domain, a previously understudied area in the literature, the current study aims to bridge the gap between the temporal and spatial domains, which have largely been studied in isolation, while maintaining methodological comparability with previous lab tasks.

Peripheral Visual Processing in ASD

Another goal of the current study was to more systematically examine the processing of targets in space at different peripheral distances from central vision. Although robust evidence exists for enhanced visual processing of features across spatial displays in those with ASD (Joseph et al., 2009; O'Riordan, 2004; O'Riordan et al., 2001; Plaisted et al., 1998), few studies have systematically measured whether this enhanced processing prevails for targets presented at all locations within a spatial array (i.e., more centrally or more peripherally in visual space). Only one study to date has systematically manipulated the distance of target stimuli from a prior spatial visual cue (Robertson, Kravitz, Freyberg, Baron-Cohen & Baker, 2013), presenting stimuli close, medium, and far distances from the visual cue on separate trials. Results revealed that adults with ASD demonstrated superior performance compared to TD peers matched by age and IQ when the target was presented nearest the visual cue, but not when it was presented farther from the cue. The authors concluded that those with ASD may experience a sharper spatial gradient of visual attention (i.e., "tunnel vision"), exhibiting enhanced processing of visual information at a focused spatial location in which attention is drawn to, but perhaps not in the periphery. When interpreting these results, it is important to note that other research has demonstrated that individuals with ASD have more difficulty disengaging from a visually cued location than TD peers (Landry & Bryson, 2004; Wainright-Sharp & Bryson, 1993). If this experiment excluded the visual cue, and targets appeared directly after the fixation (i.e., similar to traditional visual search tasks), perhaps the enhanced spatial acuity would be applied to the target, rather than the cue, in those with ASD, regardless of its location on the screen.

In contrast, several studies have found that in fact peripheral processing in ASD might also be enhanced. Evidence for this comes from a study showing increased sensitivity to peripherally presented checkerboards in children with ASD, as measured by EEG (Frey et al., 2013) as well as by a study demonstrating decreased accuracy of centrally presented targets when peripherally presented distractors shared similar features (i.e., same color; Burack, 1994). Together, these findings suggest that individuals with ASD are more attuned to visual information presented in the periphery relative to their TD peers. While there is clearly something different about peripheral visual processing in ASD, the current literature leaves an open question as to whether processing of *target* stimuli in the visual periphery is enhanced or impaired in ASD. In fact, there are no studies to date that have specifically manipulated the peripheral distance of targets from central fixation and measured accuracy using targets and distractors that differ from one another by discriminable feature-based properties. This was an important investigation within the current study.

Relationships Between Sensory Processing, Perception, and ASD Symptomology

Although the literature clearly provides evidence for differential abilities in the domain of visual perception in individuals with ASD relative to TD peers, how these relate to actual symptoms of ASD including sensory features of autism (e.g., hypersensitivity) may be useful in several ways. Understanding whether there is a relationship between perceptual processing abilities and ASD symptomology may help to characterize and predict the functional abilities of individuals with different levels of ASD severity and inform interventions as well as educational supports and strategies that may be most appropriate for a particular individual.

As sensory and perceptual features have emerged as characteristics of ASD, researchers have speculated about the relationship between atypical low-level perceptual processes and higher-order cognitive process that are also affected in ASD, such as social cognition (Robertson & Baron-Cohen, 2017; Thye, Bednarz, Herringshaw, Sartin, & Kana, 2017). Evidence has been compiled in support of a “sensory-first” approach to understanding this relationship (Robertson & Baron-Cohen, 2017), suggesting that atypical sensory processing in the early developmental period causally influences the development of social cognition in those with ASD in a feed-forward manner. Others have approached the relationship from a top-down account (Happé & Frith, 2006), suggesting that it is not sensory processing itself that is affected in ASD, but rather atypical higher-order mechanisms which serve to integrate both sensory and cognitive representations that are doing so in an altered way in those with ASD. Though much research is needed to investigate the validity of these accounts, a variety of studies have emerged which demonstrate significant relationships between either observed sensory processing behaviors or perceptual abilities, and the degree of ASD symptom severity including social communication impairment and the presence of restricted and repetitive patterns of behavior.

Linking core symptoms of ASD to sensory behaviors has most commonly been investigated through the use of validated and reliable parent-report measures. A common parent report measure that has been used to assess ASD symptoms is the Autism Spectrum Quotient (AQ; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001), which assesses a range of symptoms in the domains of social communication and restricted, repetitive behaviors. At times, ASD symptoms are measured through the use of a gold standard diagnostic assessment tools (e.g., the Autism Diagnostic Observation Schedule, Second Edition - ADOS-2; Lord et al., 2012). Additionally, a valid and reliable measure that is commonly used to assess sensory processing behaviors is the Sensory Profile (SP; Dunn, 1999) which characterizes sensory behaviors observed within and across visual, auditory, and somatosensory modalities.

Several research investigations have documented relationships between sensory processing behaviors (based on Sensory Profile ratings) and the degree of social communication impairment in children with ASD. Specifically, research has found that children with autism who exhibit a higher number of sensory behaviors across modalities (Hilton et al., 2010; Hilton, Graver & LaVesser, 2007), and particularly those who show hypo- or under-responsiveness to the sensory environment (Watson et al., 2011) also exhibited higher levels of social communication impairment, including lower language and social skill development. Other researchers have found relationships between sensory processing behaviors and the presence of restricted, repetitive behaviors (RRB) in ASD. Specifically, it has been demonstrated that children with autism who exhibit a higher number of sensory behaviors also exhibit a greater number of and more severe RRB symptoms (Chen, Rodgers & McConachie, 2009; Gabriels et al., 2008), particularly stereotypy (i.e., motor or verbal repetition) and compulsive behaviors (Boyd et al., 2011). These findings were largely consistent across children with ASD of all ages.

Although many studies have reported associations between core ASD traits and parent-reported sensory processing behaviors, fewer studies have compared ASD traits directly to performance on perceptual tasks. This smaller area of research has demonstrated that children with a higher level of overall autism symptoms, based on AQ and ADOS-2 scores, performed with higher perceptual accuracy on a feature-based temporal search task (Kopec et al., *in press*) and with more efficient feature detection thresholds (i.e., lower reaction time by set size intercepts; Joseph et al., 2009). Frey et al. (2013) also demonstrated that children with more severe RRB symptoms showed a higher level of neural responsiveness to peripherally presented visual stimuli.

Collectively, the literature in this area suggests that there is a relationship between sensory processing and core ASD symptoms, such that individuals with more atypical sensory behaviors also exhibit a higher level of social communication impairment and presence of restricted, repetitive behaviors. Similarly, a few studies have found that superior performance on perceptual tasks is related to a higher severity of these ASD symptoms. While the current study aims to further examine these relationships by correlating performance accuracy on a visual perception task with core ASD symptoms, it also aims to explore the currently poorly understood and understudied relationship (Mottron, 2019) between perceptual accuracy and clinically measured sensory behaviors. Additionally, although it has been demonstrated that ASD-related traits (as measured by symptom report measures such as the AQ) are normally distributed within the typically developing population (Hurst, Mitchell, Kimbrel, Kwapil, & Nelson-Gray, 2007; Ruzich et al., 2015), few studies have examined their relation to perceptual abilities and sensory behaviors in TD individuals, which will also be investigated in the current study.

The Current Study

Although research has investigated visual processing in ASD across space, across time, and in the periphery, few studies have investigated and manipulated these variables in combination within the same experiment. The one study that has (Robertson et al., 2013) included conditions that could have negatively impacted the performance of individuals with ASD (e.g., presenting visual cues prior to presentation of stimuli), and did not include targets and distractors that differed by discriminable stimulus features which appears to be critical in the processing enhancements found in ASD (Hagmann et al., 2016; Joseph et al., 2009; O'Riordan, 2004; O'Riordan et al., 2001; Plaisted et al., 1998). Although research from each domain provides important insight into the nature of autistic visual processing, examining them in conjunction may lead to a better understanding of the perceptual enhancements within this population, especially given that in real-world experiences, individuals must simultaneously process information across each of these domains.

In an attempt to do just this, the current study introduces a feature-based visual search task (see Figures 1 and 2 for visual diagrams) which manipulates the peripheral distance of targets from central fixation (close, medium, far) across trials, in addition to the rate at which target and distractor stimuli are presented on the screen (39, 117, 195ms). Combining findings from the previous literature, it is hypothesized that accuracy will be higher for a) slower presentation rates (main effect of presentation rate) and b) targets presented closer to the central fixation (main effect of distance), resulting in a presentation rate by distance interaction. In addition, it is hypothesized that children with ASD will outperform TD peers in overall target accuracy (main effect of group), particularly at the fastest presentation rate (group by presentation rate interaction) and at the closest distance (group by distance interaction), based on the findings of Hagmann et al. (2016) and Kopec et al. (*in press*).

Additionally, the current study will explore relationships between visual perception, as measured by performance accuracy on the experimental task, and autistic symptoms including social communication impairments and presence of restricted, repetitive behaviors and patterns of interest, measured by a parent-report scale. Although an underdeveloped topic in the literature, findings of previous studies (Frey et al., 2013; Joseph et al., 2009; Kopec et al., *in press*) suggest that higher levels of autism-related symptoms might be associated with more accurate performance on the experimental task in both children with ASD and in TD children. Similar findings in the current investigation would provide further evidence for a direct relationship between perceptual abilities and impairment in higher-order processes (i.e., social cognition) as suggested by sensory-first accounts of autism. The current study will also explore relationships between visual perceptual ability and sensory processing behaviors, which will help to clarify whether these constructs, which have been studied separately in the autism literature (Mottron, 2019), are related.

The current study has the potential to fill several gaps in the literature by making a novel contribution to the understanding of the nature of visual processing across *multiple* domains in children with ASD. In addition, the expected findings within the context of basic scientific theory regarding visual feature detection (Treisman & Gelade, 1980; Wolfe, 1994) would suggest that individuals with ASD may bear specific neurodevelopmental differences that enhance parallel processing mechanisms in the brain. An important clinical contribution of the current study is that it may help to provide a better understanding of how and whether sensory behaviors and perceptual function are related. Although the current study lacks a certain level of ecological validity in that individuals are unlikely to come across the specific stimuli presented in this experiment in the real world, it moves a step closer to real-world visual processing experiences by investigating temporal, spatial, and peripheral domains simultaneously, laying the groundwork for applied research that may have more direct clinical and educational implications.

Method

Participants

Children with autism spectrum disorder (ASD) and typically developing (TD) children were recruited through word of mouth, flyers placed in the community and delivered via school listservs, and by re-contacting previous participants at the Center for Autism Research and

Electrophysiology (CARE) Lab at Syracuse University. Children were excluded if a) their vision was impaired and non-corrected, b) they did not pass a brief colorblindness test (see Clinical Measures), or c) their performance intelligence quotient (PIQ) was below a standard score of 85, placing them more than one standard deviation below average. TD children were also excluded from participation if their parents reported a history of academic or psychiatric problems.

Eight participants with ASD with a mean age of 12.08 years (*SD* = 1.62) and 13 TD participants with a mean age of 11.34 years (SD = 3.56) were included in the final analyses. The age distributions of each group were found to violate the assumption of equal variance, and therefore a Welch t-test was used to determine that there was no significant difference in age between groups (t (17.95) = 0.66, p = 0.52). The age of participants ranged from 9.43 years to 14.18 years in the ASD group, and from 7.14 years to 16.38 years in the TD group. Importantly, research suggests that the ability to orient visual attention is fully developed by the age of 6 or 7 years (Landry, Johnson, Fleming, Crewther, & Chouinard, 2019; Woods et al., 2013), children between 7 and 17 years of age do not experience differences in distractor interference on visual search tasks (Merrill & Conners, 2013), and children between 7 and 17 years of age do not show significant differences on feature-based visual search task efficiency when targets differ from distractors by a single feature (Hommel, Li, & Li, 2004). A t-test also revealed that groups did not differ in their performance IQ (PIQ; t (18) = -0.18, p = 0.86). Matching groups by age and PIQ is common when comparing groups of individuals with developmental differences, such as ASD, to typically developing individuals, particularly when groups are being compared on nonverbal, perceptual tasks (Burack, Russo, Flores, Iarocci, & Zigler, 2012).

Lastly, the ASD group consisted of 7 males and 1 female, while the TD group consisted of 4 males and 9 females. The literature on sex differences in spatial visual processing is historically contentious, with many experiments conducted in the 1970s concluding that visual spatial abilities are superior in males (Harris, 1978; Jacklin, 1979; Lips, Myers, & Colwin, 1978). These reports have since been criticized for basing conclusions on poor methodology or small samples, while over-interpreting differences with negligible effect sizes (Caplan, MacPherson, & Tobin, 1985). Various studies and meta-analyses have reported that tasks involving mental rotation are the only types of spatial visual processing tasks that have garnered sufficient evidence of sex differences (Linn & Petersen, 1985), while robust evidence suggests that sex has no effect on spatial visualization (Linn & Petersen, 1985), spatial organization (Shah, Prados, Gamble, De Lillo, & Gibson, 2013), visual search accuracy (McGuinness & Courtney, 1983), or visual spatial perception abilities (Linn & Petersen, 1985). Thus, the unequal distribution of sex between groups is not expected to influence results of the current experiment. Detailed sample characteristics can be seen in Table 1.

A power analysis was conducted prior to the collection of data in order to determine the number of participants required to obtain reasonable statistical power to detect the expected effects. The statistical program GLIMMPSE was used to calculate the required sample size for a desired power of 0.8. Group means and standard deviations, as well as within-participant correlations across manipulations of presentation rate and distance, were estimated based on pilot data in typically developing individuals, as well as on values from previous lab experiments in which the current study is adapted from (i.e., Hagmann et al., 2016; Kopec et al., *in press*), with the expectation of medium effect sizes (i.e., $d = 0.5$) in accuracy differences between groups. Results of the power analysis suggested that 17 participants per group would be sufficient to detect the expected effects with a power level of 0.822. Accordingly, the initial goal was to enroll a minimum of 17 children with ASD and 17 TD children to participate in the experiment.

However, the final sample is slightly smaller due to several factors. First, data collection was disrupted by a global pandemic (i.e., COVID-19) causing the cancellation of a data blitz scheduled in mid-March 2020, which would have brought the sample very close to these goal numbers. Second, two participants (one from each group) demonstrated near-chance performance across all blocks of the experimental task, with accuracy scores more than two standard deviations below groups means and were therefore excluded from analyses. Finally, two prospective participants with ASD were excluded from participation due to below-threshold performance on a brief colorblindness test (which is discussed further in the Clinical Measures section below).

Clinical Measures

The Autism Diagnostic Observation Schedule, Second Edition (ADOS-2; Lord et al., 2012) was administered to all participants with a previous diagnosis of ASD (and those suspected of meeting diagnostic criteria for ASD) in order to confirm diagnosis prior to participation in the experiment. The ADOS-2 has shown strong internal consistency, test-retest and inter-rater reliability, as well as high construct and predictive validity (Lord et al., 2012). The Autism Diagnostic Interview, Revised (ADI-R; Lord, Rutter, & Le Couteur, 1994) was also administered to the parent or guardian of each participant with ASD to further confirm diagnosis prior to research involvement. The ADI-R is a reliable and valid instrument for use in children with ASD (Lecavalier et al., 2006), demonstrating high internal consistency (Lord et al., 1994), and ability to distinguish a diagnosis of autism from other developmental disorders (Lord et al., 1994; Tadevosyan-Leyfer et al., 2003). The ADI-R and ADOS-2 in combination are currently considered the gold standard for ASD diagnosis (Falkmer, Anderson, Falkmer, & Horlin, 2013). Both the ADI-R and the ADOS-2 were administered by graduate students or a licensed psychologist who have been formally trained in and have obtained research reliability on these measures. All individuals included in the ASD group met the clinical thresholds on the ADOS-2 and ADI-R, in addition to clinical judgement.

The Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II; Wechsler, 2011) was used to measure performance intelligence quotient (PIQ) in all participants. The WASI-II is a brief and reliable intelligence test containing four subtests that provide a full-scale IQ (FSIQ) standard score, a verbal comprehension index (VCI) standard score, and a perceptual reasoning index (PRI) standard score. In the current study, the PRI score served as the PIQ estimate to ensure that participants from the ASD and TD groups did not differ significantly in their nonverbal intelligence. The WASI-II has demonstrated good to excellent internal consistency in children between the ages of 6 and 16, high inter-rater and test-retest reliability, as well as acceptable to high concurrent validity with other commonly used measures of intelligence (Wechsler, 2011).

The Autism Spectrum Quotient (AQ; Baron-Cohen et al., 2001) was administered to a parent or guardian of all participants to measure autism-related symptoms. This 50-item parent-report questionnaire is commonly used as an ASD screening measure to assess five different ASD trait domains (attention switching, attention to detail, communication, imagination, and social skills). Overall scores on the AQ are normally distributed in the general population (Hurst et al., 2007; Ruzich et al., 2015), and an overall raw score of 32 is currently considered the suggested cutoff for further ASD assessment. This questionnaire has demonstrated construct validity in its significant association with clinical diagnoses of ASD (Baron-Cohen, Hoekstra, Knickmeyer, & Wheelwright, 2006), as well as satisfactory internal consistency and inter-rater reliability (Hoekstra, Bartels, Cath, & Boomsma, 2008).

Additionally, the caregiver questionnaire of the Sensory Profile (SP; Dunn, 1999) was administered to the parent or guardian of all participants. The SP is designed to evaluate children's sensory processing patterns in order to characterize areas of strength and weakness. Of particular interest to the current study was the Visual Processing subscale which is derived from parent responses on this measure that relate to how a child responds to things seen, including sensitivity to visual stimuli and attention to visual details. Normative data is available for this measure and it has demonstrated moderate convergent validity with other sensory processing measures (Dunn, 1999), strong discriminant validity with measures of general school performance (Dunn, 1999), as well as good to excellent internal consistency and test-retest reliability (Ohl et al., 2012).

Notably, AQ scores were missing from one individual with ASD, while SP scores were missing from one individual with ASD and one TD individual. Several factors contributed to this missing data including research assistant error (e.g., forgetting to give a particular measure to a parent), and abrupt discontinuation of data collection due to university closure during the COVID-19 outbreak. For example, many of the families involved in research came to the lab over several visits to complete different experiments, and therefore did not always complete all parent forms on the same visit.

Lastly, because the experiment required detection of color for accurate responding, all participants were tested for colorblindness. Notably, approximately 8% of males experience colorblindness while it is much rarer in females (McIntyre, 2002). Given the high male to female ratio in ASD, it was important to rule out colorblindness in potential participants. The most widely used colorblind test was originally developed by Ishihara (1972) and is comprised of 24 cards with a variety of colored blotches on them. Those with typical color vision are able to easily identify numbers and shapes formed by patterns of different colored ink dots on the cards. Conversely, those who experience colorblindness are unable to identify these letters and shapes accurately. Marey, Semary, & Mandour (2015) developed and tested an electronic version of the Ishihara colorblindness test to determine its accuracy when presented in this format. The electronic version of the task yielded nearly perfect results when compared to the card-based test, with 100% sensitivity and 98.78% specificity in detecting those with colorblindness. Smartphone and tablet applications using the Ishihara blots have since been developed and are now commonly used to accurately test for colorblindness. The current study used the smartphone application "Colorblindness Eye Exam Test" which is an optometrist-certified colorblindness screening that uses 24 Ishihara blots. Consistent with screening cutoffs used in the electronic and paper formats of the test (Ishihara, 1972; Marey et al., 2015), individuals who accurately identified fewer than 86% of the 24 trials (i.e., more than 3 incorrect responses) were excluded due to high likelihood of colorblindness. In the current study, two individuals were excluded for poor scores on the colorblindness test (8% and 62%) and were not allowed to participate. For those individuals who were included in the final sample, average accuracy scores on the colorblindness test were 97.5% in the ASD group and 98.2% in the TD group, which did not differ significantly.

Experimental Design

All participants completed three blocks of a visual search task that was programmed for this experiment. Each block was comprised of 99 trials (for a total of 297 trials) in which 24 stimuli were randomly presented in a scattered array on a computer screen, simultaneously. The distractor set size was fixed across trials, given the evidence that changing set size has no effect on performance on tasks in which targets differ from distractors by a single, easily discriminable feature (Treisman & Gelade, 1980). The order of blocks was randomized and counterbalanced across participants using a Latin Square approach to ensure that any practice effects would be evenly distributed across blocks in the final results.

Prior to each trial, a fixation cross was presented centrally on the computer screen for 1000ms. Next, one target stimulus (a purple letter) was presented amidst 23 distractor stimuli (black letters) on a light gray background for a fixed period of time within each block (either 39ms, 117ms, or 195ms). These presentation rates were chosen to be consistent with the presentation rates used in a slightly different temporal visual attention task (rapid serial visual presentation) conducted in the CARE lab at Syracuse University (Hagmann et al., 2016; Kopec et al., *in press*) in order to draw additional space/time comparisons for participants who choose to participate in other laboratory tasks in conjunction with the current experiment. Additionally, previous research has demonstrated that letter identification is possible at all peripheral distances used in the current study, with the exception of the faster presentation rate at the farthest peripheral distance (Seiple, Holopigian, Shnayder, & Szlyk, 2001). This was confirmed by pilot data from a small group of TD young adults ($n = 9$) who completed the experimental task and showed floor effects only at the 39ms-far manipulation. The decision to block the trials by presentation rate was made for several reasons: to maintain consistency with the experimental designs of similar tasks within the lab that will be compared to data obtained in the current study; to maintain consistency with the task designs from which the current experimental task was modified (Hagmann et al., 2016; Kopec et al., *in press*) as well as similar spatial search tasks within the literature (O'Riordan, 2004; O'Riordan et al., 2001; Plaisted et al., 1998); to facilitate future exploration of the current task in an EEG paradigm in which blocked designs are often preferred; and to mitigate distress or distraction from the task as many children with autism experience oversensitivity to subtle visual and temporal changes.

Additionally, within each block, the purple target letter was presented within specified peripheral windows from the central fixation cross (close, medium, and far). On one third of trials the purple target appeared close to (0 to 7.99 degrees visual angle), a medium distance from (8 to 14.53 degrees visual angle), or far from (14.56 to 20.68 degrees visual angle) the central fixation point. Target and distractor stimuli consisted of the letters A, B, C, D, F, H, J, K, L, N, P, R, T, V, X, and Y in size 45 font with no distractors being the same as the target letter. Following each trial, a response screen was presented containing 5 letter options (the target and 4 distractors) in black text along with the instruction “Choose the purple letter.” This method relies on recognition rather than recall of targets, minimizing the need to use working memory. A demonstration of the time course of each trial in the experimental task can be seen in Figure 1, while a depiction of the peripheral distances can be seen in Figure 2.

The independent variables in this experiment include 1) the rate at which stimuli are presented on the screen (39, 117, and 195ms) which differed by block, and 2) the distance of the target relative to the central fixation cross (close, medium, and far) which differed by trial in equal proportions across all three blocks. The dependent variable measured was detection accuracy of the target across these manipulations, which was compared between groups (ASD and TD).

Apparatus

All stimuli were presented using Matlab on a Dell P2414H with a resolution of 1920 by 1080 pixels and with a 60 Hz refresh rate. The entire computer screen subtended 50.32 degrees horizontally and 29.58 degrees vertically from participants' eyes. Close stimuli were presented within 0 to 7.99 degrees visual angle from the center of the screen in all directions, and the stimuli themselves subtended a visual angle of 1.27 to 1.28 degrees. Medium stimuli were presented within 8 to 14.53 degrees visual angle from the center of the screen in all directions, and the stimuli themselves subtended a visual angle of 1.21 to 1.25 degrees. Finally, far stimuli were presented within 14.56 to 20.68 degrees visual angle from the center of the screen in all directions, and the stimuli themselves subtended a visual angle of 1.14 to 1.21 degrees. The experiment was initiated and programmed using Stream, a Matlab toolbox that uses Psychophysics toolbox (Brainard, 1997).

An SR Research Ltd. Eyelink 1000 chin and forehead rest device was used to ensure that visual angles were held consistent throughout the experimental task and across participants. The device was clamped to the tabletop and the bottom of the chin rest was kept exactly 12 inches above the tabletop, making the center of the computer monitor at eye level. Tape was placed on the tabletop to mark the edges of the chin rest clamp and the computer monitor to ensure a consistent visual experience across participants. The forehead rest and chair height were adjusted as needed. The distance of the chin rest from the screen (at eye level) was 22 inches.

The luminance of the LCD computer monitor as well as of the testing room were measured using a Gossen Mavo-Monitor instrument. Five separate measurements were taken for each. Computer screen measures were: 25.8, 25.6, 28.0, 27.3, and 26.7 cd/m^2, for an average of 26.7 cd/m^2 and a range of 25.6-28.0 cd/m^2. Testing room measures were: 4.23, 4.94, 3.95, 3.93, and 4.10 cd/m^2 for an average of 4.23 cd/m^2 and a range of 3.93-4.94 cd/m^2. The lighting of the room was kept consistent across participants with the lights on at the dimmest setting. A blackout board covered the small window in the room to prevent natural light from entering. Notably, many recent visual search experiments in the literature do not report luminance levels. This may be due to findings of negligible variance in visual acuity across a vast range of screen luminance levels on modern LCD monitors as compared to older CRT monitors (Menozzi, Lang, Näpflin, Zeller, & Krueger, 2001; Takahashi, Lida, Nishioka, & Kubota, 1984), in addition to the fact that refresh rates of LCD monitors extend beyond the temporal resolution of the human visual system and do not produce a visual "flicker" effect, like many CRT monitors do, which have previously been found to influence eye movements and overall visual search performance (Kennedy, Brysbaert, & Murray, 1998; Menozzi et al., 2001). Nonetheless, reporting of luminance values is crucial to facilitate future replication and extension of research.

Procedure

The following study procedures were approved by the Institutional Review Board (IRB) through the Office of Research Integrity and Protections at Syracuse University. Participants in the ASD group were first administered the Autism Diagnostic Observation Schedule, Second Edition (ADOS-2) by a trained graduate student and their parent or guardian was administered the Autism Diagnostic Interview, Revised (ADI-R) by a licensed psychologist to confirm a diagnosis of ASD. All participants (including TD participants) were then administered the Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II) to measure performance IQ and to facilitate participant matching. However, given that IQ is relatively stable in early to middle childhood (Schneider, Niklas, & Schmiedeler, 2009), and that retesting children on the same intelligence test within a short period may yield invalid scores (possibly impacting tri-annual school-based psychoeducational evaluations), children who had previously been administered the WASI-II in the lab within the past two years did not complete this measure, and previous scores were used for matching purposes.

Participants were then taken into the testing room and the color blindness test was administered to them on the iPhone application. Participants then completed the experimental task and were provided breaks, as needed, in between blocks of trials. An experimenter remained in the room to enter the verbal responses of participants on the keyboard. This was done to keep children focused and looking at the screen throughout the task, and to minimize potential confounds of incorrect key strokes. In other words, this allowed participants to simply say the target letter they saw rather than having to remember it and look away from the screen to find the correct letter on the keyboard. This type of procedure has been found to increase effort and focus and decrease the length of the task in other experiments conducted in the lab (Kopec, Russo, Antshel, Fremont, & Kates, 2018).

The parent or guardian of each participant completed the Autism Spectrum Quotient (AQ) and the Sensory Profile (SP) questionnaires while their child participated. A research assistant explained the instructions for each measure, answered questions, and checked that the measures were completed appropriately. Upon completion of the study, participants were paid $10 per hour for their participation in the experiment.

Results

Overview of Data Analyses

A series of statistical tests were carried out in order to evaluate the hypotheses of the current study. First, extensive descriptive statistics were conducted in order to characterize and compare the ASD and TD groups across variables such as age, IQ scores, and symptom scores on parent-report measures.

Additionally, a three-way repeated measures ANOVA with within-subjects factors of presentation rate (39ms, 117ms, 195ms) and distance (close, medium, far) and a betweensubjects factor of group (ASD, TD) was originally planned to examine main effects and interactions between these variables in relation to task accuracy. Inspection of the data revealed floor effects (i.e., near-chance level accuracy; 20%) at the "far" distance across groups and presentation rates. One-sample t-tests confirmed that mean accuracy scores at the "far" distance, in each group and at each presentation rate, were not significantly different from chance ($ps > 0.05$), and this distance was therefore removed from the analysis, leaving only the "close" and "medium" distances.

Although the repeated measures ANOVA was planned a priori, additional statistical tests were conducted after considering the final dataset. Due to the unexpected discontinuation of data collection in response to the COVID-19 pandemic, the final sample was smaller than anticipated, resulting in reduced statistical power to detect the hypothesized effects. Moreover, the repeated measures ANOVA relies on several assumptions that are very difficult to obtain or accurately assess with small samples, including normally distributed data, equal variance across groups, and identification and removal of outliers. Notably, the final dataset included small and unequal sample sizes, and variance was found to be unequal across groups at several rate by distance combinations, with the smaller (i.e., ASD) group often showing more variance than the larger (i.e., TD) group. After considering several alternative options, Welch's t-tests were chosen to examine group differences at each presentation rate by distance combination (i.e., 39ms-close, 39ms-medium, 117ms-close, 117ms-medium, 195ms-close, 195ms-medium). Welch's t-test does not assume or require equal variances among groups and has been found to maintain acceptable Type I error rates when groups have unequal variances (de Winter, 2013; Delacre, Lakens, & Leys, 2017), even when groups are of unequal size (Ruxton, 2006). The Welch test has also been found to show a power advantage over alternatives (i.e., Student's t-test and Wilcoxon rank-order test) in the specific case of unequal sample sizes combined with unequal variances (de Winter, 2013), making it the preferable choice for the current dataset.

It can be argued that there are few substitutes for obtaining a large enough sample and adequate power to examine expected effects. Notably, even Welch's t-test may not be sufficient to detect existing effects in the current study, if the effects are not large (de Winter, 2013). However, when considering the limitations of alternative tests, Welch's t-test will provide the most accurate and statistically sound assessment of the limited data collected in the current experiment and provide guidance for continued data collection and future research directions.

Additional exploratory analyses were conducted to examine the relation between performance on the visual task and autism-related symptoms (i.e., raw scores obtained from various parent-report measures), in order to determine whether perceptual enhancements are related to, and perhaps developmentally influence, core autism symptoms. Specifically, a correlation matrix using Spearman rank correlations was conducted to examine correlations between Total AQ score, AQ Attention to Detail score, AQ Attention Switching score, AQ Social Skills score, AQ Communication score, the SP Visual Processing subscale score, and task accuracy scores. Spearman rank correlations are considered most appropriate when comparing scores from rating scales, in which the meaning between values is somewhat arbitrary (Aggarwal & Ranganathan, 2016). They are also preferable with small samples when group variances are unequal, because, unlike Pearson correlations, they do not assume equal variance among groups (Ruscio, 2008). They are also often recommended over Pearson correlations when the assumption of normality is violated, or when testing small samples in which the determination of normality is difficult (Bishara & Hittner, 2017; Ruscio, 2008), and are robust to potential outliers. Spearman rank correlations are also robust against Type 1 error inflation and therefore family-wise error corrections were not applied. 95% confidence intervals around Spearman's rho (r_S) were also calculated, as they have been shown to be accurate even with small sample sizes and when data is non-normal, and can aid in the interpretation of correlations in lieu of relying solely on *p*-values (Bishara & Hittner, 2017).

To reduce the number of exploratory correlations, task accuracy scores were collapsed across distance (i.e., close and medium), resulting in one average accuracy score per participant at each presentation rate (39, 117, 195ms). Correlations were conducted across both the ASD and TD groups, as ASD symptom scores have been shown to be normally distributed within the typically developing population (Hurst et al., 2007; Ruzich et al., 2015) as well as in individuals with autism (though scores tend to be higher overall). Although these correlations should be considered exploratory, it was expected that task accuracy scores would be positively correlated with Total AQ score, AQ Attention to Detail score, AQ Attention Switching score, AQ Social Skills score, and AQ Communication score. Additionally, it was expected that task accuracy would be negatively correlated with SP Visual Processing subscale scores, in which lower scores indicate more visual processing atypicalities and enhancements. These results would suggest that more accurate detection of visual features is related to more elevated symptoms and traits of ASD.

Descriptive Statistics

Descriptive data including group means and standard deviations of variables of interest as well as internal consistency (Cronbach's alpha) of each group's questionnaire scores can be viewed in Table 1, while boxplots of score distributions within each group, and across groups (for correlation purposes), are presented in Figure 3a-f.

Welch's t-tests were used to evaluate group differences among variables. Detailed sample characteristics are presented in the Participants section of the Method, but to reiterate briefly, 8 participants with ASD and 13 TD participants were included in the final analyses. Welch's t-test revealed no significant difference in age ($t(17.95) = 0.66$, $p = 0.52$) or performance IQ ($t(11.78) = -0.18$, $p = 0.86$) between groups. The ASD group had a mean PRI standard score of 111.57 (*SD* = 10.98), while the TD group had a mean PRI score of 112.46 (*SD* = 10.37). Conversely, the TD group had significantly higher VCI ($t(9.79) = -3.70$, $p = .004$) and FSIQ scores ($t(9.03) = -2.86$, $p = .02$) than the ASD group, suggesting that verbal abilities were not equivalent between groups. Specifically, the ASD group had an average VCI score of 94.14 (*SD* = 14.40), and an average FSIQ score of 102.86 (*SD* = 12.13), while the TD group had an average VCI score of 117.15 (*SD* = 10.88) and an average FSIQ score of 117.46 (*SD* = 8.18). Importantly, task accuracy scores did not significantly correlate with age, PRI score, VCI score, or FSIQ score at any presentation rate by distance combination ($ps > .05$).

Welch's t-tests revealed that groups differed significantly in Total AQ score ($t(14.93) = 5.71$, $p < .001$), with the ASD group having higher scores ($M_{ASD} = 27.14$, $SD_{ASD} = 5.11$) than the TD group ($M_{TD} = 12.23$, $SD_{TD} = 6.34$). The ASD group also had significantly higher scores on the AQ Social Skills subscale ($t(15.92) = 3.37$, $p = 0.004$), the AQ Communication subscale ($t(11.69) = 3.85$, $p = 0.002$), and the AQ Attention Switching subscale ($t(16.16) = 4.25$, $p < .001$) compared to TD peers. Groups did not differ significantly in their scores on the AQ Attention to Detail subscale ($t(8.05) = 1.24$, $p = 0.25$).

A Welch's t-test revealed that the ASD and TD groups did not differ significantly in their average SP Visual Processing subscale scores ($t\ (11) = -1.60$, $p = 0.14$). Specifically, the ASD group had an average raw Visual Processing score of 33.14 (*SD* = 8.13), while the TD group had an average score of 39 (*SD* = 6.88). Lower scores on this scale indicate more visual processing atypicalities and enhancements.

Task Accuracy

Visual representations of group accuracy scores across close and medium distances are presented separately at presentation rates of 39ms (Figure 4), 117ms (Figure 5), and 195ms (Figure 6), while boxplots of score distributions within each group are presented in Figure 7a-f.

Assumptions of the repeated measures ANOVA were checked prior to conducting the task accuracy analysis. As noted, one participant from each group was removed due to near-chance accuracy performance across manipulations. After removing these outliers, inspection of accuracy boxplots revealed one additional outlier in the ASD group at 117ms-medium and 195ms-close, and one outlier in the TD group at 39ms-close. These participants were kept in the analysis due to the prior outlier removal process as well as the difficulty in accurately identifying non-normality and outliers in small samples (de Winter, 2013). Furthermore, results of the ANOVA did not change when these participants were removed. Accuracy data were normally distributed in the ASD group at all presentation rate by distance combinations, as assessed by Shapiro-Wilk's test of normality (ps > 0.05). Accuracy scores in the TD group were also normally distributed at all presentation rate by distance combinations (ps > 0.05), except at 39ms-close ($p = 0.04$) and 195ms-close ($p = 0.04$). However, as previously mentioned, accurate determinations of normality are difficult to obtain in small samples. Groups demonstrated equal variance at each presentation rate as assessed by Levene's Test for Equality of Variances (ps > .05), although it is important to note that differences in variance approached significance at 117ms-medium ($p = .16$), 195ms-close ($p = .08$) and 195ms-medium ($p = .06$), and that Levine's test is known to perform with inflated Type II error rates (i.e., failure to reject the hypothesis that variance between groups is equal) when groups are small and unequal in size (Delacre et al., 2017). Mauchly's Test of Sphericity was found to be violated only for the main effect of presentation rate and the presentation rate by group interaction term, and Greenhouse Geiser corrections were reported instead (notated as GG).

Results of the repeated measures ANOVA revealed a main effect of presentation rate ($F_{GG}(2, 38) = 62.58$, $p < .001$, $\eta^2_p = 0.77$) in which overall accuracy increased as presentation rate increased (i.e., became slower). More specifically, post hoc tests revealed that accuracy at 39ms was significantly lower than accuracy at 117ms ($p < .001$) and 195ms ($p < .001$), which were also significantly different from each other ($p < .001$). There was also a main effect of distance ($F(1, 19) = 248.56$, $p < .001$, $\eta^2_p = 0.93$) such that overall accuracy decreased as the target was presented farther from central fixation. More specifically, accuracy on close distance trials was significantly higher than accuracy on medium distance trials ($p < .001$). The overall repeated measures ANOVA did not reveal a main effect of group ($F(1, 19) = 0.62$, $p = 0.44$, $\eta^2_p = 0.03$), suggesting that the ASD and TD groups performed similarly in their overall target accuracy across manipulations of rate (39, 117, 195 ms) and distance (close, medium).

The repeated measures ANOVA also did not reveal any significant interactions. That is, there were no interactions found between presentation rate and distance ($F(2, 38) = 2.23$, $p = 0.12$, $\eta^2_p = 0.11$), group and presentation rate ($F_{GG}(2, 38) = 0.16$, $p = 0.85$, $\eta^2_p = 0.009$) or group and distance ($F(1, 19) = 0.39$, $p = 0.54$, $\eta^2_p = 0.02$).

Welch's t-tests were also conducted to investigate group differences in accuracy at each presentation rate by distance combination (i.e., 39ms-close, 39ms-medium, 117ms-close, 117ms-medium, 195ms-close, 195ms-medium) as a more statistically sound approach to investigate these differences given the small, unequal samples. Results of these t-tests revealed significant group differences at the close distance when stimuli were presented for 195ms ($t(19) = 2.2$, $p = 0.04$, Cohen's $d = 0.93$), with ASD participants ($M_{ASD} = 0.972$, $SD = 0.041$) outperforming TD participants ($M_{TD} = 0.919$, $SD = 0.069$). However, significant group differences were not observed at other presentation rate by distance combinations, although the ASD group performed numerically higher at all but the 195ms-medium manipulation. Specifically, groups were found to perform similarly at 39ms-close ($t(10.9) = 0.61$, $p = 0.54$, Cohen's $d = 0.30$), 39ms-medium ($t(14.2) = 0.58$, $p = 0.56$, Cohen's $d = 0.27$), 117ms-close ($t(17.5) = 0.58$, $p = 0.58$, Cohen's $d = 0.25$), 117ms-medium ($t(18.9) = 0.72$, $p = 0.48$, Cohen's $d = 0.48$), and 195ms-medium ($t(9.4) = -0.43$, $p = 0.68$, Cohen's $d = -0.20$).

Correlations between Task Accuracy and ASD-related Symptoms

An exploratory correlation matrix was conducted across both the TD and ASD groups to examine relations between task accuracy (collapsed across close and medium distances) and autism-related symptoms. As noted, Spearman rank correlations were used, which are more appropriate than Pearson correlations in the context of small sample size and non-normal distributions, including skewed and bimodal distributions, and potential outliers. Inspection of correlation plots revealed clear monotonic relationships among the variables tested, an important assumption of the Spearman correlation. Detailed results of the correlation matrix can be viewed in Table 2, while boxplots displaying score distributions for questionnaire scores used in the analysis are shown in Figure 3a-f.

Autism Spectrum Quotient (AQ) and Task Accuracy

Several significant correlations were observed between task accuracy scores and scores on the AQ. Specifically, Total AQ score was significantly positively correlated with task accuracy at the 39ms presentation rate ($r_S = 0.56$, 95% CI = 0.17 – 0.80, $p = 0.02$), indicating that a higher level of overall autism-related traits was related to higher accuracy at this rate (Figure 8a). Conversely, Total AQ score was not significantly correlated with task accuracy at 117ms (r_S = 0.28, 95% CI = -0.17 – 0.63, p = 0.24) or 195ms (r_S = 0.26, 95% CI = -0.19 – 0.70, p = 0.27).

Significant correlations were also observed between task accuracy and specific subscale scores of the AQ (Figure 8b-e). For instance, task accuracy was significantly positively correlated with the Attention to Detail subscale score at the 195ms presentation rate (r_S = 0.51, 95% CI = 0.10 – 0.77, p = 0.02). However, correlations between accuracy and AQ Attention to Detail scores were not significant at the 39ms (r_S = 0.33, 95% CI = -0.12 – 0.67, p = 0.16) and 117ms (r_S = 0.31, 95% CI = -0.14 – 0.65, p = 0.19) presentation rates. Task accuracy was also significantly positively correlated with the AQ Attention Switching subscale score at the 39ms presentation rate (r_S = 0.59, 95% CI = 0.21 – 0.81, p = 0.006), but not at the 117ms (r_S = 0.24, 95% CI = -0.21 – 0.61, p = 0.32) or 195ms (r_S = 0.14, 95% CI = -0.31 – 0.54, p = 0.55) presentation rates. Furthermore, task accuracy was significantly positively correlated the AQ Social Skills subscale score at the 39ms presentation rate (r_S = 0.50, 95% CI = -0.08 – 0.82, p = 0.02), but not the 117ms (r_S = 0.09, 95% CI = -0.58 - 0.52, p = 0.70) or 195ms (r_S = 0.17, 95% CI = -0.28 – 0.56, p = 0.48) presentation rates. Lastly, task accuracy was not significantly correlated with AQ Communication subscale scores at any of the presentation rates, including 39ms (r_S = 0.33, 95% CI = -0.12 – 0.67, p = 0.15), 117ms (r_S = 0.21, 95% CI = -0.24 – 0.59, p = 0.37), and 195ms (r_S = 0.03, 95% CI = -0.41 – 0.46, p = 0.90).

Sensory Profile and Task Accuracy

The SP Visual Processing subscale score was found to be significantly negatively correlated with task accuracy at the 39ms presentation rate (r_S = -0.47, 95% CI = -0.75 – -0.05, p = 0.04), which is depicted in Figure 8e. Conversely, SP Visual Processing scores were not significantly correlated with task accuracy at the 117ms (r_S = -0.11, 95% CI = -0.52 – 0.34, p = 0.65) or 195ms (r_S = -0.12, 95% CI = -0.52 – 0.33, p = 0.63) presentation rates.

Discussion

The current study set out to test the spatial and temporal limits of enhanced visual perception in children with autism spectrum disorder, in order to move toward a more realistic assessment of these abilities in a world where our environments do, in fact, unfold simultaneously over both space and time. An additional goal was to explore the relationships between enhanced perceptual abilities and core ASD symptoms, as well as sensory features of ASD, an area that is currently poorly understood and understudied (Mottron, 2019). While the current study has several limitations, which are discussed individually in subsequent sections below and reiterated in the Limitations section, the most pressing of these is the smaller than expected sample size, limiting the ability to draw strong conclusions about the data. Much of the discussion is therefore written with this caveat in mind. Nonetheless, care was taken to employ stringent statistical methods to glean from the data the most accurate and sound conclusions possible in order to guide continued data collection and future research directions.

The Limits of Enhanced Visual Perception in ASD Across Space and Time

Previous investigations have documented enhanced visual perception across space (O'Riordan, 2004; O'Riordan et al., 2001; Plaisted et al., 1998) and time (Hagmann et al. 2016; Kopec et al., *in press*) in children with ASD. Collectively, these findings begged the question of just how far this autistic advantage might persist if spatial and temporal dimensions were examined in combination, more consistent with real-world experiences. The current study aimed to shed light on this question using a novel design that manipulated the peripheral distance of target purple letter stimuli in space, and the temporal rates at which they were presented.

Across both groups, perceptual accuracy significantly increased as presentation rate decreased (i.e., was slower) and as targets were presented closer to central fixation, suggesting that the experimental manipulations were effective. Additionally, the ASD group demonstrated significantly higher accuracy relative to the TD group at the slowest presentation rate tested (195ms) when targets were "close" to the center of the screen. Conversely, there were no observed group differences in accuracy at presentation rates of 117ms or 39ms when targets appeared "close" to the center of the screen, or at any of the presentation rates when targets were a "medium" distance from the center of the screen. Therefore, the hypothesis that children with ASD would outperform TD children at the fastest rate (39ms) when targets appeared close to central fixation was unsupported. Notably, while not statistically significant, the ASD group performed with numerically higher accuracy relative to the TD group on 5 out of the 6 rate by distance manipulations. This suggests that perceptual advantages might exist in those with ASD beyond a particular temporal window in which they are most prominent, but with very small effect sizes, which may emerge as significant with a larger sample and increased statistical power. These results provide important insight into the nature of perceptual processing, both in individuals with ASD and TD individuals, in the context of simultaneous spatial and temporal constraints.

Comparisons with the Spatial and Temporal Visual Processing Literature

The experimental task used in the current study is, in many ways, a marriage between tasks previously used in the literature which have been able to meaningfully characterize autistic perception in the spatial and temporal domains, separately. In comparing results of the current study to the findings of other *spatial* visual search experiments that have investigated autistic perceptual advantages, there are several task differences that must be considered. First, many other spatial search experiments (O'Riordan, 2004; O'Riordan et al., 2001; Plaisted et al., 1998) did not manipulate the temporal component of stimulus presentation and presented stimuli in a spatial array for a period of time until a response was provided. Furthermore, the primary measure of interest in many of these tasks was not accuracy, but reaction time – the amount of time it took participants to provide a response following the onset of stimulus presentation. Additionally, many of these tasks required detection of features, but not identification of an object. That is, many of the tasks presented trials in which the target was present or absent, with accuracy measures reflecting the ability to detect the presence or absence of a target on a particular trial, rather than the ability to identify details about the target, as was the case in the current study (i.e., reporting which letter was purple). Moreover, targets in these tasks varied by features other than color, and included targets of different size, shape, orientation, etc. Finally, many previous investigations, despite being interested in characterizing visual perceptual abilities across space in ASD, did not systematically manipulate the distance of targets from central fixation. making it impossible to evaluate whether perceptual enhancements in ASD are more robust at close or proximal distances.

Drawing comparisons with the existing literature examining visual perceptual abilities in those with ASD within the *temporal* domain is made easier by the large amount of overlap between the task used in the current study and those used in previous investigations, including the tasks used by Hagmann et al. (2016) and Kopec et al. (*in press*). For instance, all of these tasks utilized identical stimuli (purple and black letters of the same text size) which were presented on the same light grey backdrop, using the same computers and equipment. The current study also shares an overlapping stimulus presentation rate (39ms) with Kopec et al. (*in press*). The critical difference is that previous tasks (Hagmann et al., 2016; Kopec et al., *in press*) isolated the temporal domain of visual processing by presenting all stimuli sequentially in a fixed, central, spatial location (i.e., RSVP), while the current study introduced spatial manipulations by presenting target and distractor stimuli simultaneously at varying spatial locations on the screen (close, medium, and far), while maintaining temporal manipulations by presenting stimuli at varying rates.

Borrowing from both spatial and temporal search task designs (Hagmann et al., 2016; Kopec et al., *in press*; O'Riordan, 2004; O'Riordan et al., 2001; Plaisted et al., 1998), the current study presented stimuli in a spatial array on a computer screen at varying presentation rates, while measuring the identification accuracy of a featurally unique target presented at systematically manipulated peripheral distances. Findings of the current study do not refute previously reported findings of enhanced visual perceptual abilities across space, but do suggest that there is likely a temporal limit to these enhancements, perhaps especially visible on difficult search tasks such as this one. Results also suggest that, when spatial search is required, the temporal window in which the autistic perceptual advantage exists may differ from the 39-65ms window previously reported in tasks without a spatial component (Hagmann et al., 2016; Kopec et al., *in press)*. Results demonstrate that, although children with and without ASD are able to detect and identify feature-based targets at close and medium distances from the center of the screen (within 14.53 degrees visual angle) and at very fast presentation rates (39ms and 117ms) with above chance accuracy, children with ASD do not show an advantage relative to TD peers. When the presentation rate was slowed to 195ms, children with ASD began to show a perceptual advantage, but only when the target was presented very close to the center of the screen.

Importantly, results suggest that both children with and without ASD engaged in efficient, parallel processing (Treisman, 1982; Treisman & Gelade, 1980; Wolfe, 1994) of targets when they were close to or a medium distance from central fixation, as evidenced by the relatively high performance accuracy at all 3 rapid presentation rates used in the experiment. However, children from both groups seemed unable to accurately identify targets presented far from central fixation, demonstrating chance level accuracy at all presentation rates at this distance. Given that the manipulations of presentation rate and distance were effective in the current study, coupled with the finding of a perceptual advantage in autism emerging at the slowest presentation rate and at the closest distance, children with ASD would likely demonstrate perceptual advantages further into the periphery, within some specific temporal window, if given more processing time.

Relevant to the interpretation of these findings, Seiple et al. (2001) previously demonstrated that letter *detection* is possible at all locations on the computer screen in which targets were presented here, even at rates as fast as 39ms, but that the temporal window of letter *identification* increases as letters are presented further from central fixation. Specifically, Seiple et al. (2001) reported that, while TD adults were able to identify letters presented at a peripheral distance of 14 degrees (the inner boundary of the “far” distance in the current study) within approximately 70ms, letter identification was only possible within 180ms at 22 degrees (which is just beyond the outer boundary of the “far” distance used here), suggesting that identification of targets across this distance would be more challenging, and sometimes not possible (i.e., at the fastest rate of 39ms). These results suggest that, in the current study, children were likely able to *detect* targets at all distances, but they may have required more time to *identify* (i.e., bind the color purple to the correct letter) targets at “far” distances in particular.

It is also possible that saccadic eye movement would have been required in these cases. Research suggests that saccadic eye movements can be initiated as quickly as 80-90ms following the presentation of a stimulus (Kotowicz, Rutishauser, & Koch, 2010) and that one only needs to fixate on a target following a saccadic eye movement for 10ms in order to accurately identify it (Kirchner & Thorpe, 2006). In fact, the temporal constraints of target identification presented by Seiple et al. (2001) suggest that target *detection* does not likely require saccades at any peripheral distances on a computer screen, while *identification* at "far" distances may. Importantly, while previous studies have documented differential processing of peripheral stimuli in ASD (Burack, 1994; Frey et al., 2013), these investigations leave open the question of whether individuals on the spectrum demonstrate greater *detection* of these stimuli, or if they are actually binding stimulus features and *identifying* them.

Future research should consider utilizing eye tracking technology in order to determine how far into the periphery individuals can identify purple letters on the computer screen without requiring saccades, the additional time needed when a saccade is required, and whether these factors differ for individuals with ASD relative to TD peers. Investigating these questions will help to elucidate whether peripheral processing (in the absence of a saccade) or foveal (i.e., central) processing (following a saccade to a stimulus) is enhanced in ASD in relation to detection and identification of feature-based targets. While considerable work is still needed to answer these questions, the novelty of the specific manipulations used in the current study help to shed light on the temporal and spatial limitations of visual perceptual advantages in ASD, and suggest that the temporal window in which autistic perceptual advantages exist likely shifts with the added requirement of spatial search, emerging by rates of 195ms, and possibly before, but only when targets are close to the location of visual fixation. In addition to including eye tracking methods, future research will also need to include additional, slower presentation rates to better evaluate autistic perceptual advantages farther into the visual periphery.

Relationships between Perceptual Accuracy, ASD Traits, and Sensory Symptoms

In addition to examining the visual perceptual abilities of children with ASD across both spatial and temporal domains, another important goal of the current study was to explore the relationship between these visual perceptual abilities and ASD-related traits, as well as specific sensory processing behaviors.

Visual Perceptual Accuracy and ASD Traits

As previously discussed, various research studies have documented significant relationships between the core symptoms of ASD and sensory features of ASD. That is, studies have reported that individuals with higher levels of social communication impairment (Hilton et al., 2007; Hilton et al., 2010; Watson et al., 2011) and restricted, repetitive patterns of behavior (RRB; Boyd et al., 2011; Chen et al., 2009; Gabriels et al., 2008) also exhibited more atypical sensory behaviors. While these studies drew their conclusions exclusively from parent-report and clinician-rated scales, other studies have compared autism-related traits directly to performance on perceptually-based visual tasks and found that individuals with more social communication impairment (Joseph et al., 2009) and RRB symptoms (Frey et al., 2013; Joseph et al., 2009) demonstrated superior perceptual abilities on a variety of visual tasks.

In line with these previous findings, the current study found several significant relationships between core ASD symptoms and visual perceptual abilities. Specifically, when collapsing across both groups, individuals with higher accuracy at the fastest rate of 39ms also exhibited higher overall ASD symptom scores (Total AQ score), and specifically more impaired social skills and more difficulty with attention switching. At the slowest speed, those with higher accuracy were found to pay closer attention to details. While the Total AQ score is comprised of all 50 items on the AQ scale and reflects a composite of ASD-related traits, each individual subscale contains domain-specific items. For instance, the Social Skills subscale includes items related to social impairment (e.g., finding social situations difficult, finding it hard to make friends, having difficulty interpreting facial expressions and intentions of others, and preferring to do things alone), while the Attention Switching score relates more strongly to RRB symptoms (e.g., preferring to do things the same way over and over, becoming strongly absorbed in one thing, becoming fixated on prescribed interests, and preferring regular routines). The Attention to Detail subscale also measures RRB symptoms (e.g., fascination with dates and numbers), while also capturing some level of perceptual differences (e.g., noticing things that others do not including subtle visual and auditory changes). The significant relationships observed between perceptual accuracy and each of these AQ scores suggest that there is a relationship between enhanced visual perceptual ability and both social and RRB autism symptom domains.

An important considerations to note in the interpretation of these particular findings is that, although the ASD and TD groups differed significantly in their average AQ scores, with the exception of the AQ Attention to Detail score, there was considerable overlap between groups as can be seen in the boxplots presented in Figure 3a-e, and group data generally resemble normal distributions in Total AQ score, consistent with previous reports (Hurst et al., 2007; Ruzich et al., 2015). Overall, these findings suggest that ASD-related traits and visual perceptual ability are meaningfully linked across both ASD and TD populations.

Visual Perceptual Accuracy and Sensory Symptoms

The current study also aimed to explore the relationship between parent-reported sensory features of ASD and visual perceptual abilities as measured by task performance. To do so, parent ratings from the Visual Processing subscale of the Sensory Profile (SP) were correlated with task accuracy. The SP Visual Processing subscale assesses various sensory behaviors within the visual domain, including hyper-sensitivity to light, careful or intense visual inspection of objects, and difficulty with gestalt visual processing. Lower scores on this subscale indicate a higher level of these sensory behaviors in the visual domain. Collapsing across both groups, children with lower SP Visual Processing scores performed with higher accuracy on the experimental task at the presentation rate of 39ms, but not at slower presentation rates. Similar to the significant AQ correlations, this relationship occurred in the absence of group differences in accuracy, suggesting that visual sensory behaviors that are common in those with ASD may be meaningful across both the ASD and TD population in their relation to visual perceptual ability.

While the current findings suggest a relationship between perceptual ability and sensory behaviors, their relation in ASD has been understudied and questioned by some (Mottron, 2019). Part of the issue is that, although sensation and perception are closely linked processes that are difficult to disentangle and are sometimes even used interchangeably, they have been conceptualized and studied separately over the past several decades within the ASD literature. Mottron (2019) has pointed out that the sensory processing literature overemphasizes a deficit-based hyper-/hypo-sensitivity framework which suggests that atypicalities in sensory and perceptual processing in ASD lead to impairment in functioning. As such, many clinical scales designed to assess sensory features of autism subscribe to this deficit-focused, medical model and highlight functional impairment. In fact, items on the SP Visual Processing subscale use terminology such as “gets frustrated by” and “is bothered by” when asking parents to rate their child’s visual sensory symptoms.

While sensory symptoms may be bothersome to individuals with ASD at times (e.g., closing eyes in the presence of bright lights or covering one’s ears in the presence of loud noises), Mottron (2019) points out that there are far more examples and indications of sensory features leading to positive affect in those with ASD. For example, individuals with ASD often seek out and find pleasure in visual sensory stimulation, as evidenced by prolonged visual fixation and close visual inspection of objects. Mottron (2019) suggests that these sensory and perceptual behaviors should, therefore, be considered strengths that likely contribute to autistic intelligence and world knowledge, rather than a deficit, which would be more consistent with research on enhanced perceptual abilities in those with ASD, particularly in the visual domain (Hagmann et al., 2016; Joseph et al., 2009; Kopec et al., *in press*; O'Riordan, 2004; O'Riordan et al., 2001; Plaisted et al., 1998). Therefore, the deficit-focused language used on the SP may not accurately capture perceptual strengths that these individuals may possess. It will be important to examine relationships between these variables within the ASD population alone when more data are obtained.

Neural Correlates of Enhanced Visual Perception in ASD

Although the current study did not utilize tools to directly examine neural correlates of perceptual enhancement, results can be interpreted within the context of existing findings in the literature on this topic. As previously noted, the perceptual processing differences often observed in individuals with ASD likely stem from neuroanatomical and neurofunctional differences in this population. Two theoretical perspectives currently dominate the field: a) the sensory-first perspective (Robertson & Baron-Cohen, 2017) which posits that early sensory processing brain regions may develop atypically in children with ASD and directly influence the development of higher-order ASD symptoms (i.e., social cognition) in a feed-forward manner, and b) the top-down perspective (Happé & Frith, 2006), which suggests that higher-order neural mechanisms which serve to integrate both sensory and cognitive representations develop atypically in those with ASD, and that these higher order differences might lead to compensatory lower-level mechanisms, such as enhanced perception.

Although there is evidence for neural alterations in higher-order brain regions that contribute to perception (Keehn, Brenner, Palmer, Lincoln, & Müller, 2008; Keehn, Nair, Lincoln, Townsend, & Müller, 2016; Keehn, Shih, Brenner, Townsend, & Müller, 2014), substantial evidence of atypical neural architecture and functionality of primary sensory regions in those with ASD has also emerged. Some researchers have pointed out that changes in higher-order neural substrates can be explained by the sensory-first approach, in which initially altered sensory regions are thought to influence the development of these higher-order regions, but that alterations in primary sensory regions are difficult to explain from a top-down perspective, which posits that higher-order mechanisms account for perceptual differences in those with ASD (Robertson & Baron-Cohen, 2017). Recent evidence of atypical neural architecture and functionality in primary sensory regions of the brain in ASD have led some to believe that the sensory-first approach is more viable than top-down accounts (Robertson & Baron-Cohen, 2017). This argument is made somewhat complicated by the fact that higher-order processes, such as attention, modulate neural responses in primary sensory regions. However, the perception of individuals with autism has been shown to be less influenced by higher-order cognitive biases, including attention and prior experiences, than TD peers (Baron-Cohen, Ashwin, Ashwin, Tavassoli, & Chakrabarti, 2009; Mottron, Dawson, & Soulières, 2009; Mottron, Dawson, Soulières, Hubert, & Burack, 2006b), and structural changes in primary sensory regions, as well as differential activation of sensory regions, make a compelling argument for the sensory-first perspective.

A recent meta-analysis used activation likelihood estimation (ALE) to investigate fMRI activation patterns in different brain regions for a variety of non-social perceptual tasks (Jassim, Baron-Cohen, & Suckling, 2020). The authors compiled fMRI data from studies that investigated perceptual processing of individuals with ASD compared to TD controls on basic (e.g., visual search, target detection, oddball) and more complex (e.g., reward anticipation, learning, response inhibition) perceptual tasks in visual, auditory, and tactile modalities. When looking at basic visual perception tasks alone (the category in which the current study would fit), individuals with ASD showed significantly higher levels of neural activation in early, sensory regions of the brain compared to TD controls, including the lateral occipital cortex, visual cortex, inferior parietal lobule, cerebellum, premotor and primary motor cortices, and the secondary somatosensory cortex. Conversely, TD controls showed more activation in frontal and parietal areas, including the middle and inferior frontal gyrus, precuneus, precentral gyrus, central opercular cortex, and superior parietal lobule. Results were generally the same when looking at basic perceptual tasks in other modalities (i.e., auditory and tactile), as well as when looking at the more complex perceptual tasks, suggesting that differential neural activity in early sensory regions of the brain are likely responsible for behaviorally observed perceptual differences in ASD, across sensory modalities.

One study, which specifically investigated neural activation patterns using fMRI during a difficult visual search task, aimed to determine which regions were more or less activated in those with ASD compared to TD controls (Keehn et al., 2008). Behaviorally, those with ASD did not demonstrate faster reaction times than TD peers, but did evidence more efficient search (measured by reaction time by set size slopes) of targets that differed from distractors only by orientation (all were black Ts). Authors suggest that differences in search intercepts were likely not found, as they have been elsewhere (Joseph et al., 2009) due to the lack of easily discriminable features in the task. Additionally, those with ASD were found to show more activation in both higher-order frontoparietal regions, as well as low-level occipital regions, compared to TD controls. These results provide support for differential processing occurring in early sensory brain regions, but also suggest that higher-order attentional control processes may be differentially activated in ASD.

Although the current study did not use imaging techniques to directly measure functional neural differences during perceptual visual processing, the evidence presented here suggests that alterations in early sensory regions such as the primary visual cortex likely contribute to significant findings. Research suggests that it takes at least 50ms for a visual stimulus to loop from the retina, to the "top," higher-order processing regions of the brain, and back, in order to confirm what one has seen (Potter, Wyble, Hagmann, & McCourt, 2014). The fact that significant relationships were found between ASD traits and task accuracy at the very fast presentation rate of 39ms, but not slower rates, may indicate that individuals with a higher level of autistic traits possess enhanced low-level brain mechanisms, allowing them to identify targets with higher accuracy at rates (i.e., less than 50ms) which preclude the ability to "double-check." This result is also remarkably consistent with the findings of Kopec et al. (*in press*), in which correlations were observed between ASD traits and visual perceptual ability at very fast presentation rates, even when TD and ASD groups did not differ in task accuracy. These findings are most consistent with the "sensory-first" account of autism, suggesting that alterations in early sensory brain regions might causally influence the development of core autism symptoms including social communication impairment. While it has been demonstrated that attentional biases can modulate visual perception from the moment a stimulus is seen in TD adults (Kelly, Gomez-Ramirez, & Foxe, 2008), research suggests that the perceptual experiences of individuals with autism are less influenced by cognitive biases, including attention (Baron-Cohen et al., 2009; Gonzalez-Gadea et al., 2015).

A fruitful avenue for future research, which may allow these questions to be tested directly, would be the inclusion of EEG methods to investigate real-time neural responsiveness while participants engage in the experimental task. Event-related potentials (ERPs) represent patterns of neural activation with high temporal resolution and are obtained using EEG by aggregating activation patterns across experimental trials. Two ERPs have been identified in the literature as related to pre-attentive perceptual detection of visual deviants (i.e., visual targets that differ from distractors by some featural or categorical component; Kimura, Ohira, & Schröger, 2010). A robustly studied ERP component, the deviant related negativity, has since been found to be comprised of two distinct ERP components, the visual N1 and the visual mismatch negativity (MMN), which overlap temporally and spatially. Using standardized low-resolution brain electromagnetic tomography (sLORETA), Kimura et al. (2010) demonstrated that the neural generators of the visual N1 were mostly primary visual areas, while generators of the MMN were non-primary visual areas and prefrontal regions. Relatedly, Koivisto, Grassini, Salminen-Varparanta, and Revonsuo (2017) identified two distinct ERPs, one associated with accurate *detection* of a stimulus at 200-300ms post-stimulus, and another associated with accurate *identification* of a stimulus (e.g., what number it was) emerging around 400ms post-stimulus. Examining these ERPs may help to determine whether stimulus features are better *detected* in ASD, even when the stimulus cannot be accurately identified. While not yet studied in the ASD population, investigating these ERP components during visual tasks like the one used in the current study could help to provide further neural evidence of enhanced visual perception in ASD, and better understand its neural correlates.

Clinical Implications

Although the current study takes a basic scientific approach to understanding perceptual abilities in children with ASD, it is a crucial steppingstone in elucidating important, clinically relevant implications for children and their daily functioning. Individuals with ASD have been described as “seeing the trees, but not the forest” in that they are often attuned to perceptual details at the expense of the global whole (Robertson & Baron-Cohen, 2017). From this perspective, autistic perceptual abilities cannot be viewed simply as a strength or a weakness, as they are dependent on particular task demands and the environment.

Findings of the current study suggest that children with ASD may be more apt to perceive visual features of objects in space, within some temporal constraints. Although these findings are preliminary, if they are to hold true with a larger sample, they have important implications for children with ASD and how they interact with their environments. For instance, in a classroom setting there are countless visual stimuli that children may be asked to attend to, draw their attention away from, or search for amongst the various competing objects in the room. While TD children are generally able to navigate these highly visually stimulating settings with success, children with ASD are often reported to experience sensory overload and learning difficulties within the classroom (Caldwell, 2017). While the current study and previous investigations (Hagmann et al., 2016; Joseph et al., 2009; Kopec et al., *in press*; O’Riordan, 2004; O’Riordan et al., 2001; Plaisted et al., 1998) highlight an enhancement in visual perceptual abilities over space and time in this population, these skills may *hinder* functioning in the context of a classroom and other settings in which a large number of visual stimuli with competing features exist. For instance, being more attuned to visual features of the environment may lead to distractibility and difficulty focusing and maintaining attention on the task at hand. This, in turn, may lead to distress and dysregulation, which are commonly reported in children with ASD in over-stimulating environments (Caldwell, 2017).

On the other hand, while atypical sensory features of autism have been historically conceptualized through a deficit-based lens focused on the impairments that may arise from hyper- or hypo-sensitivity to sensory input, Mottron (2019) points out the many strengths of atypical perceptual processing in ASD, including contributions to autistic intelligence and world knowledge. More specifically, autistic perception of complex visual and auditory stimuli is thought to increase language learning capabilities (e.g., through echolalia and hyperlexic behaviors) and lead to enhanced nonverbal intelligence, including visual spatial problem solving (Roberts, 2014; Soulières et al., 2009). Because the unique perceptual abilities of children with ASD may help or hinder their ability to learn, depending on the context, it will be important to develop interventions that take this into account and don't over-generalize these abilities as a universal strength or weakness. For instance, on a task that requires students to focus on a one stimulus at a time, it might be important to block out external distracting stimuli for children with ASD. On the other hand, altering educational tasks in a way that emphasizes the perceptual strengths of children with ASD may be helpful. Perhaps incorporating instructional activities that involve visual search for feature-based stimuli (word searches, scene searches, classroom scavenger hunts, etc.) could be used to facilitate success and generate interest in learning new material in children with ASD.

While these types of interventions hold promise in improving educational and functional outcomes for children with ASD, the exact nature of the perceptual abilities of this population is still not fully understood. An important next step to better understanding the boundaries of enhanced perceptual abilities in ASD in the visual domain is to examine them in additional lab-based perceptual tasks in order to provide further clarity and guidance for future applied experiments that might include more complex and ecologically relevant stimuli (e.g., finding a red book in a classroom scene). Taking these important steps will hopefully lead to real-world applications and development of functionally-informed interventions to help children with autism use their strengths to best learn and succeed.

Results of the current study also provide some preliminary insight into the relationship between sensory processing behaviors typical of ASD, and visual perceptual abilities, as well as implications for how these features should be clinically conceptualized. Whereas results demonstrate a relationship between atypical visual sensory behaviors and enhanced ability to detect and identify visual features of stimuli (at 39ms), the strength of this relationship may be negatively impacted by deficit-focused language on the SP (Mottron, 2019), particularly for children with ASD. While the ASD group was too small to accurately assess the within-group relation between these variables, it will be important to explore this further when more data are obtained. Clinicians and researchers should consider developing sensory processing measures that not only highlight the impairments that may arise due to sensory symptoms, but also the strengths or positive attributes that may be experienced. This may change how clinicians (and the rest of the world) view autism and provide an avenue for the development of clinical and school-based interventions that focus not only on accommodating weaknesses, but also bolstering strengths of individuals with ASD. Taking a strengths-based approach may positively impact individuals with ASD by fostering and building on their strengths, as well as influence perceptions and attitudes of family members, teachers, and community members, who unfortunately may have been primed to focus only on the deficits of these individuals.

Finally, if early perceptual processing differences in ASD are in fact responsible for the development of higher-order symptoms including social communication impairment, this could change how we think about, and intervene with individuals on the spectrum. While more and more evidence appears to support this sensory-first account of ASD, early interventions that find creative ways to manipulate the sensory world in order to capitalize on the perceptual strengths of children with ASD (e.g., explicitly using sensory stimuli to draw attention to and foster social learning and engagement) may be helpful in altering the developmental trajectory of social communication symptoms.

Limitations and Future Directions

The current study has several limitations, many of which were discussed in prior sections, but will be briefly reiterated here. First, the final sample included in the analyses was smaller than planned, primarily due to the unanticipated COVID-19 pandemic which caused an abrupt halt in data collection. Importantly, data collection will continue whenever possible in order increase the statistical power to detect the hypothesized effects. A larger sample size will likely be more representative of the ASD and TD populations, will increase confidence in use of the planned statistical analyses (e.g., repeated measures ANOVA), and will allow for stronger conclusions about the nature of autistic perception across space and time.

The current study was also limited by the presentation rates that were used in the experimental task. The presentation rates were chosen based on results of pilot data, which demonstrated that 9 TD adults were able to detect targets with accuracy above chance at each rate by distance combination, with the exception of the “far” distance at the fastest presentation rate, and children with ASD have previously been found to perform with similar accuracy as adults on a feature-based perceptual in the temporal domain (Hagmann et al., 2016). The finding that children in both groups were largely unable to detect targets presented at the "far" distance (i.e., beyond 14.56 degrees visual angle) at the 3 presentation rates tested suggests that perceptual functions required for identification of feature-based stimuli with spatial and temporal constraints might improve with development from childhood to adulthood. Interestingly, task accuracy was not correlated with age in the current sample at any presentation rate by distance combination, suggesting that these abilities are perhaps stable across the ages tested in the study, from 7 to 16 years old, but these conclusions are limited by the small sample size and correlations did not include the "far" distance where floor effects were observed and developmental differences might be most apparent. Future investigations should include slower presentation rates in order to accurately assess perception further into the periphery in children. Additionally, given that perceptual accuracy was quite high at the slowest presentation rate of 195ms when targets were presented "close" to the center of the screen, it may be important to separately assess perceptual processing at close, medium, and far distances with distinct presentation rates for each. This will help to determine the temporal boundaries of visual enhanced perceptual processing at each of these peripheral distances in children with ASD.

Another potential limitation of the current study is the blocking of trials by presentation rate. Although this decision was made to be consistent with previous visual perception experiments conducted in the lab and elsewhere, to facilitate a future EEG imaging investigation, and to mitigate distress for children with ASD who may be more sensitive to subtle temporal changes, this type of trial blocking may not have been optimal. For instance, future investigations might consider blocking trials by distance (close, medium, and far) with randomized presentation rates within each block such that participants would be primed to expect targets to appear at a particular distance on every trial during a given block. This type of priming might engage higher-order attentional mechanisms that may enhance perceptual functioning at the very rapid presentation rates used in the experiment. Although current research points to atypical functionality of low-level visual brain regions as being the probable explanation for perceptual enhancements observed in those with ASD (Robertson & Baron-Cohen, 2017), studies have also found increased frontoparietal activation in those with ASD during visual search tasks (Keehn et al., 2008, 2016, 2014), which may help to modulate processing in low-level visual regions. Alternatively, it may be useful to abandon trial blocks altogether, and to randomize presentation rate and distance across all trials to achieve true randomization. This would also be more ecological, given that in the real world, we don't always have control or knowledge about the timing and location of stimuli that may appear in our environments.

An additional limitation of the current study is that only one visual feature was used to assess the perceptual accuracy of participants. That is, the target and distractor stimuli used in the experiment differed by the feature of color. Although additional visual search experiments that used a variety of feature-based stimuli with targets differing from distractors by color, size, shape, orientation, etc., consistently found perceptual advantages in individuals with ASD compared to TD peers (O'Riordan, 2004; O'Riordan et al., 2001; Plaisted et al., 1998), it will be important to utilize different types of stimuli in the novel task that was introduced here. The feature of color, again, was chosen for consistency purposes with previous experiments conducted in the lab. However, it is possible that the temporal boundaries of enhanced detection and identification of targets in ASD may differ by feature type. Therefore, including additional feature-based stimuli in future investigations will be crucial.

Although the current study provides some insight into the relationships between core ASD symptoms, visual sensory behaviors of ASD, and visual perceptual abilities as measured by task accuracy, there are several limitations to the interpretation of these findings. First, the correlations between these variables were collapsed across groups, and across peripheral distances, to reduce the number of correlations run. Although both ASD and TD populations have been found to show normally distributed variability on the measures of ASD traits (Hurst et al., 2007; Ruzich et al., 2015) and sensory behaviors (Dunn, 1999) used in the current study, the means of these distributions differed significantly on 4 out of 6 of the subscales used in these correlations. However, groups did not differ significantly in their task accuracy when collapsing across close and medium peripheral distances, making these correlations somewhat less ambiguous. Nonetheless, it would be ideal to have adequate sample size and statistical power to assess these relationships within each group, as it is possible that differences exist.

Finally, the current study is limited by its inclusion of autistic individuals who represent a specific phenotype of the overall ASD population. That is, individuals included were of average to above average intellectual ability. Importantly, only 38% of individuals with ASD have Full Scale Intelligence Quotient scores above a standard score of 85, while just as many children with ASD (38%) are considered intellectually disabled (with standard IQ scores below 70; CDC, 2020). Many children with comorbid ASD and intellectual disability would have difficulty participating in the experimental task used in the current study. Nonetheless, it is important to note that the results reported here may not be representative of the ASD population overall, but of a specific subset of the population. Future research should continue striving to find ways for individuals from across the spectrum to participate in research to address this common limitation in the field.

Table 1

Descriptive Statistics

	Group	N	Mean	*SD*	Cronbach's alpha	*p*-value (Welch's t-test)
Age (years)	ASD	8	12.083	1.618	-	0.52
	TD	13	11.327	3.556	-	
VCI	ASD	7	94.143	14.404	-	0.004
	TD	13	117.154	10.877	-	
PRI	ASD	7	111.571	10.983	-	0.86
	TD	13	112.462	10.365	-	
FSIQ	ASD	7	102.857	12.130	-	0.02
	TD	13	117.462	8.181	-	
Total AQ score	ASD	7	27.143	5.113	0.57	< 0.001
	TD	13	12.231	6.340	0.82	
AQ Social Skills	ASD	7	4.857	1.676	0.17	0.004
	TD	13	1.846	2.267	0.78	
AQ Attention Switching	ASD	7	7.286	1.604	0.27	< 0.001
	TD	13	3.615	2.219	0.68	
AQ Attention to Detail	ASD	7	5.286	3.147	0.82	0.25
	TD	13	3.692	1.750	0.50	
AQ Communication	ASD	7	6.429	2.507	0.67	0.002
	TD	13	2.000	2.345	0.80	
SP Visual Processing	ASD	7	33.143	8.133	0.86	0.14
	TD	12	39.000	6.876	0.91	

Notes. VCI = Verbal Comprehension Index; PRI = Perceptual Reasoning Index; FSIQ = Full-Scale Intelligence Quotient; AQ = Autism Spectrum Quotient; SP = Sensory Profile. VCI, PRI, and FSIQ scores are standard scores, while AQ and SP scores are raw scores.

Table 2

Correlation Matrix Results

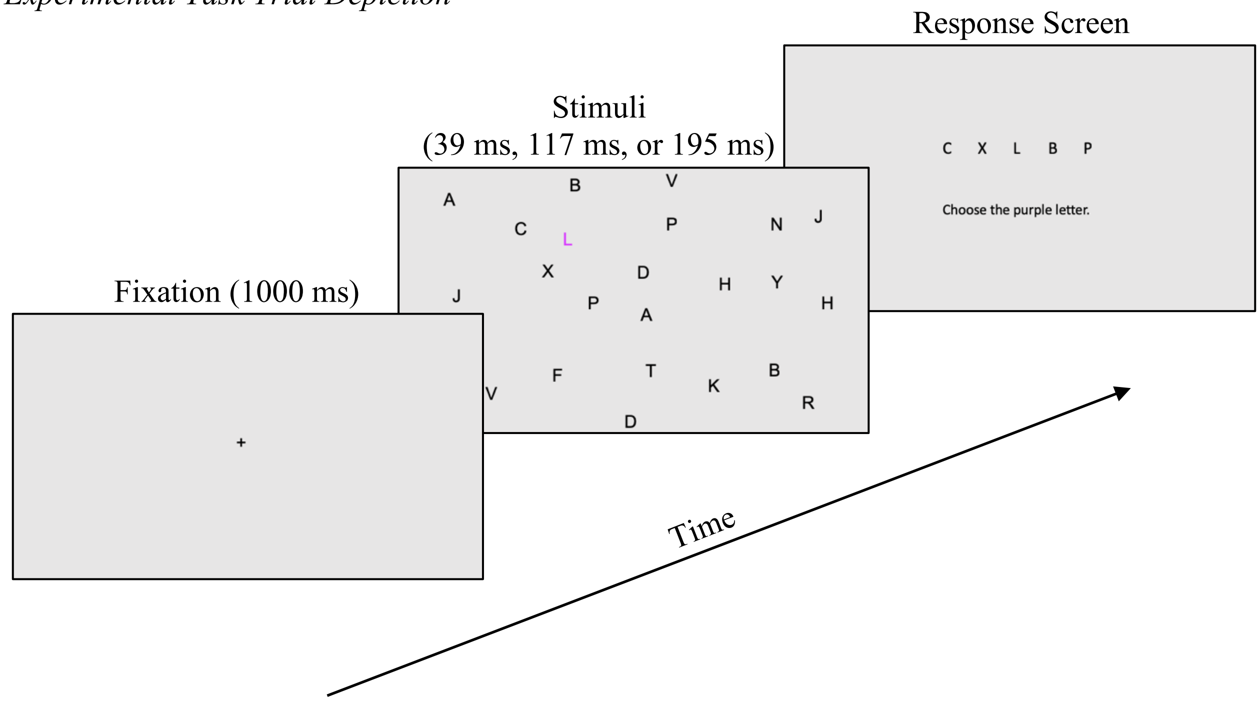
	Accuracy		
	39ms	117ms	195ms
Total AQ			
r_S	0.56 *	0.28	0.26
95% CI	0.17 – 0.80	-0.17 – 0.63	-0.19 – 0.70
p	0.02	0.24	0.27
AQ: Attention to Detail			
r_S	0.33	0.31	0.51 *
95% CI	-0.12 – 0.67	-0.14 – 0.65	0.10 – 0.77
p	0.16	0.19	0.02
AQ Attention Switching			
r_S	0.59 **	0.24	0.14
95% CI	0.21 – 0.81	-0.21 – 0.61	-0.31 – 0.54
p	0.006	0.32	0.55
AQ Social Skills			
r_S	0.50 *	0.09	0.17
95% CI	-0.08 – 0.82	-0.58 - 0.52	-0.28 – 0.56
p	0.02	0.70	0.48
AQ Communication			
r_S	0.33	0.21	0.03
95% CI	-0.12 – 0.67	-0.24 – 0.59	-0.41 – 0.46
p	0.15	0.37	0.90
SP Visual Processing			
r_S	-0.47*	-0.11	-0.12
95% CI	-0.75 – -0.05	-0.52 – 0.34	-0.52 – 0.33
p	0.04	0.65	0.63

Notes. r_S = Spearman's rho; AQ = Autism Spectrum Quotient, SP = Sensory Profile

* $p < .05$, ** $p < .01$

Figure 1

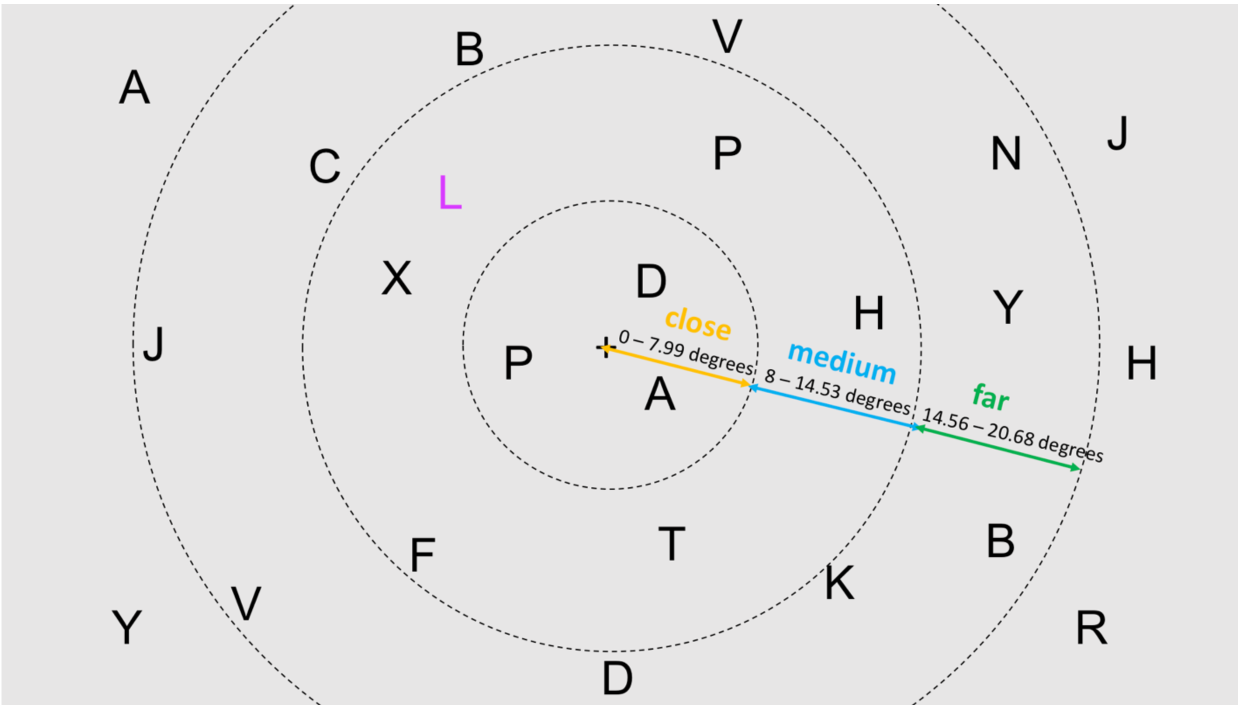
Experimental Task Trial Depiction



Note. This figure depicts the time course of one trial of the visual search task used in this experiment.

Figure 2

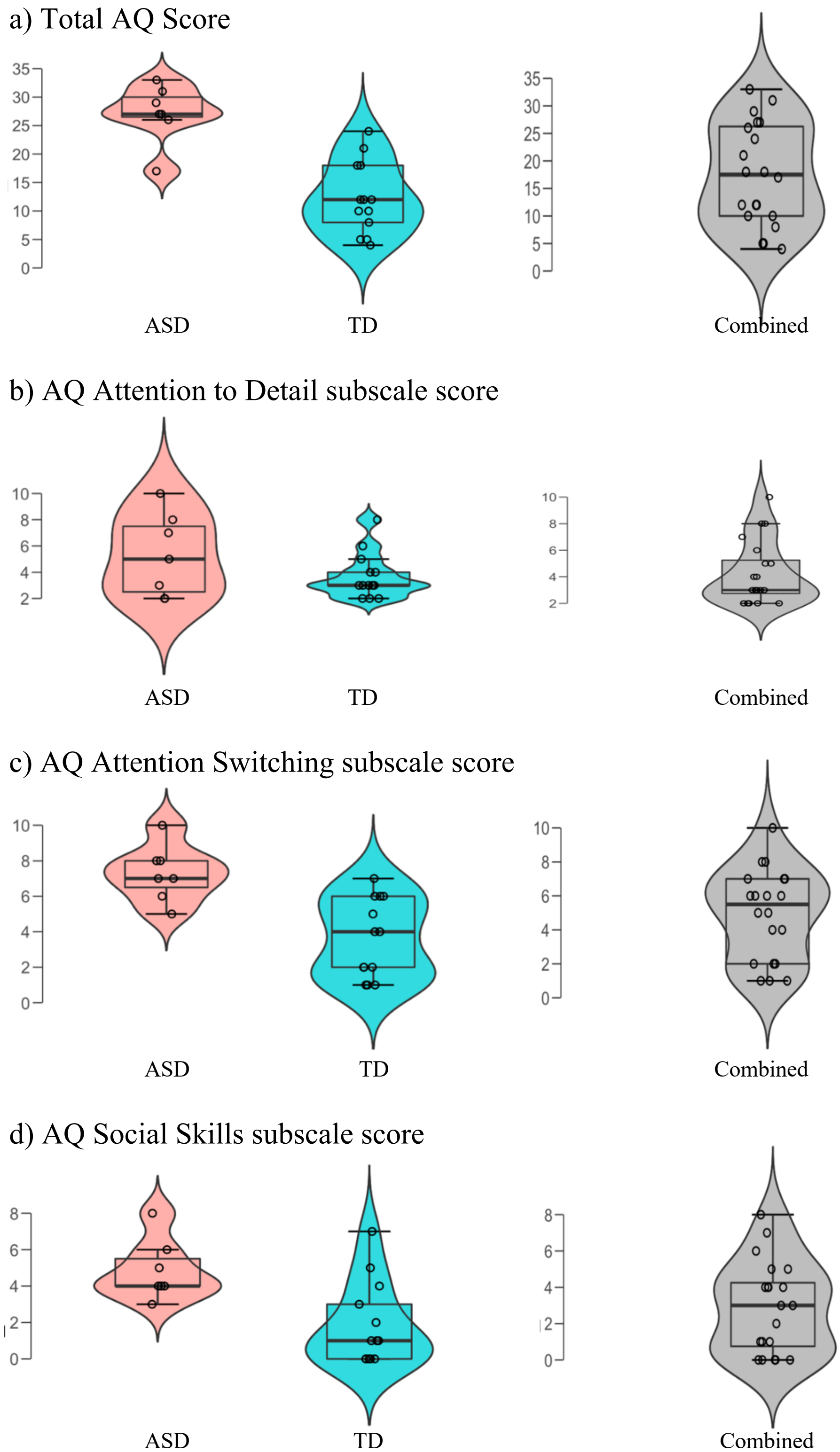
Depiction of Peripheral Distances



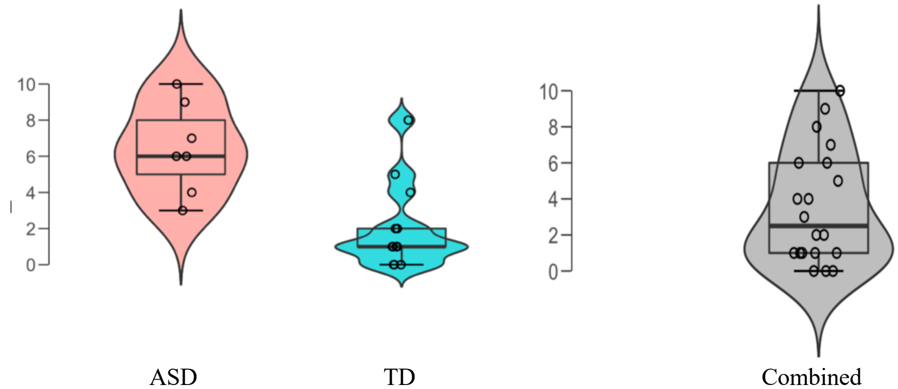
Note. This figure illustrates the distance ranges of targets in the experimental task. Purple targets appear close (0 to 7.99 degrees visual angle), medium (8 to 14.53 degrees visual angle), and far (14.56 to 20.68 degrees visual angle) from the central fixation on one third of trials each. While distractor stimuli were presented outside of these windows at times, targets were always presented within one of these windows. Dotted lines are for illustration only, and do not appear in actual experimental trials.

Figure 3

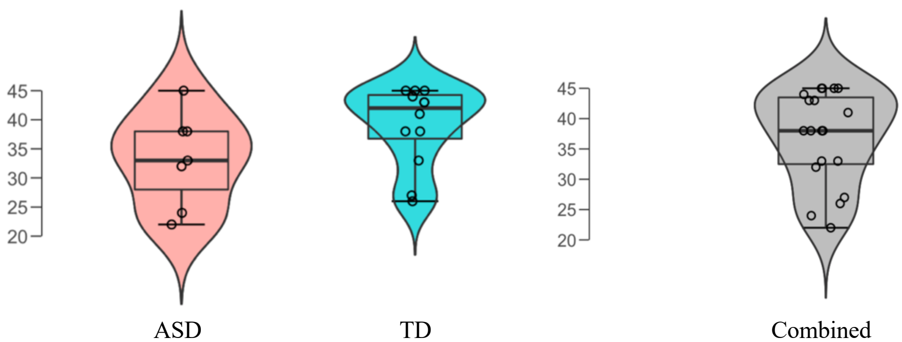
Boxplots of Questionnaire Data



e) AQ Communication subscale score



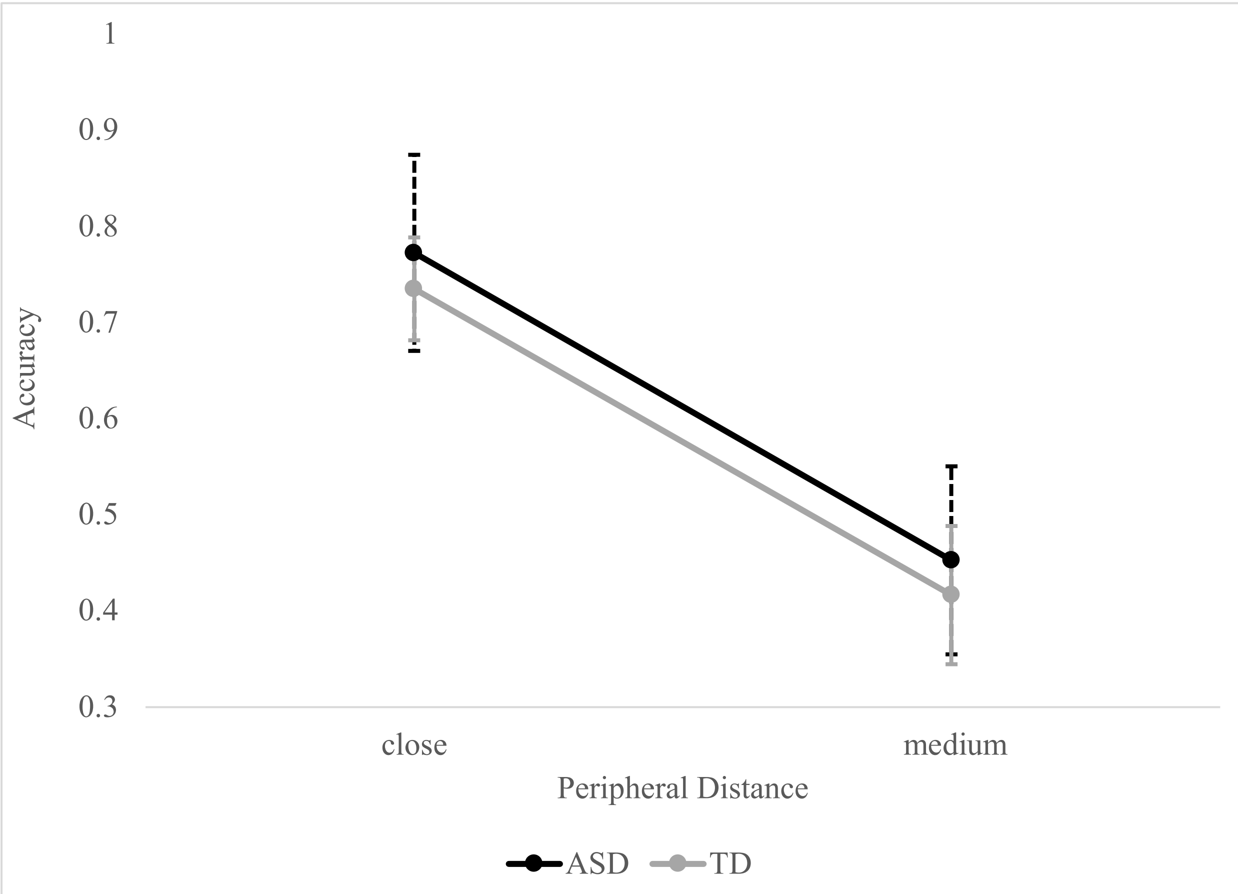
f) SP Visual Processing subscale score



Note. Boxplots depict the distribution of questionnaire raw scores in the ASD (red) and TD (blue) groups separately, as well as in both groups combined (gray) for correlation purposes.

Figure 4

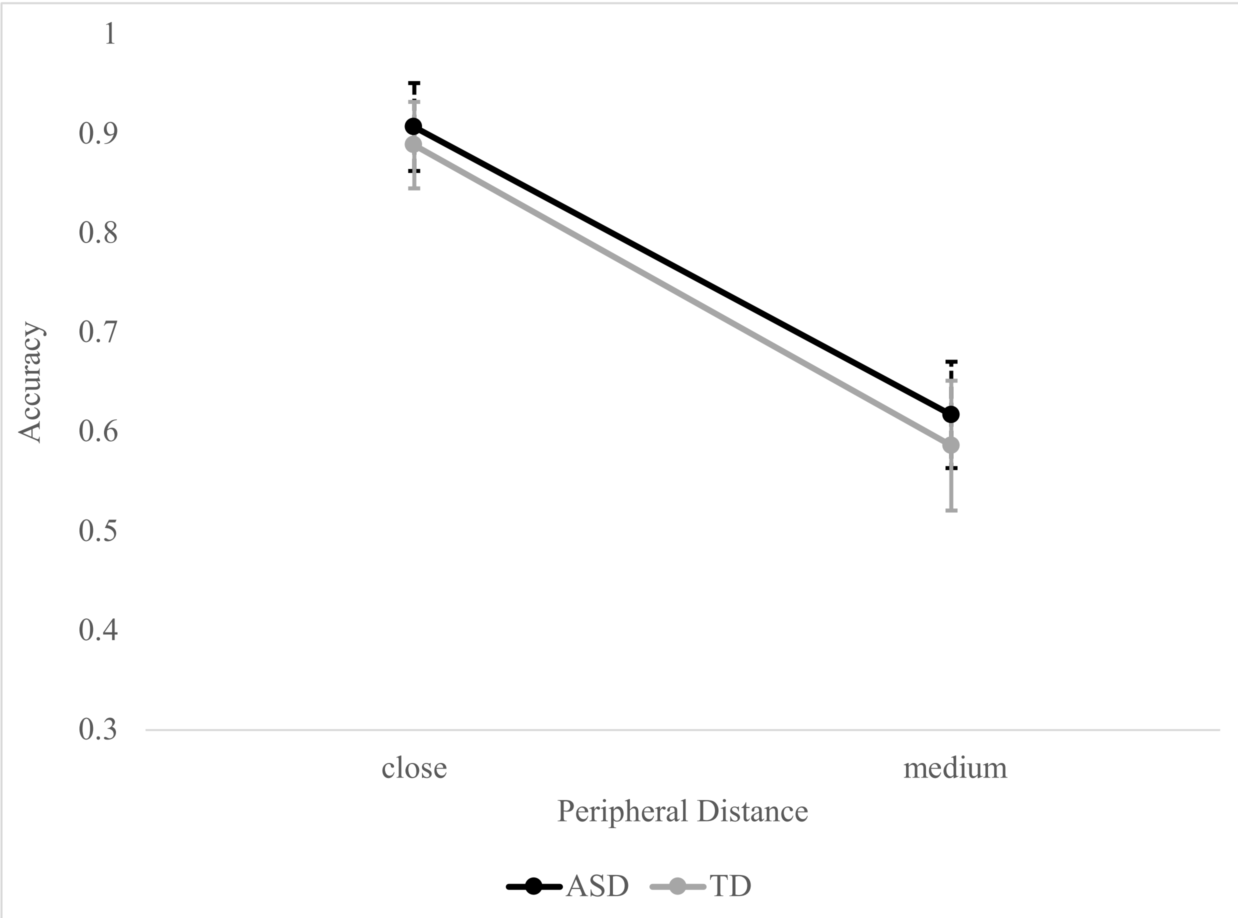
Accuracy by Distance Scores at 39ms Presentation Rate



Note. Error bars reflect 95% Confidence Intervals.

Figure 5

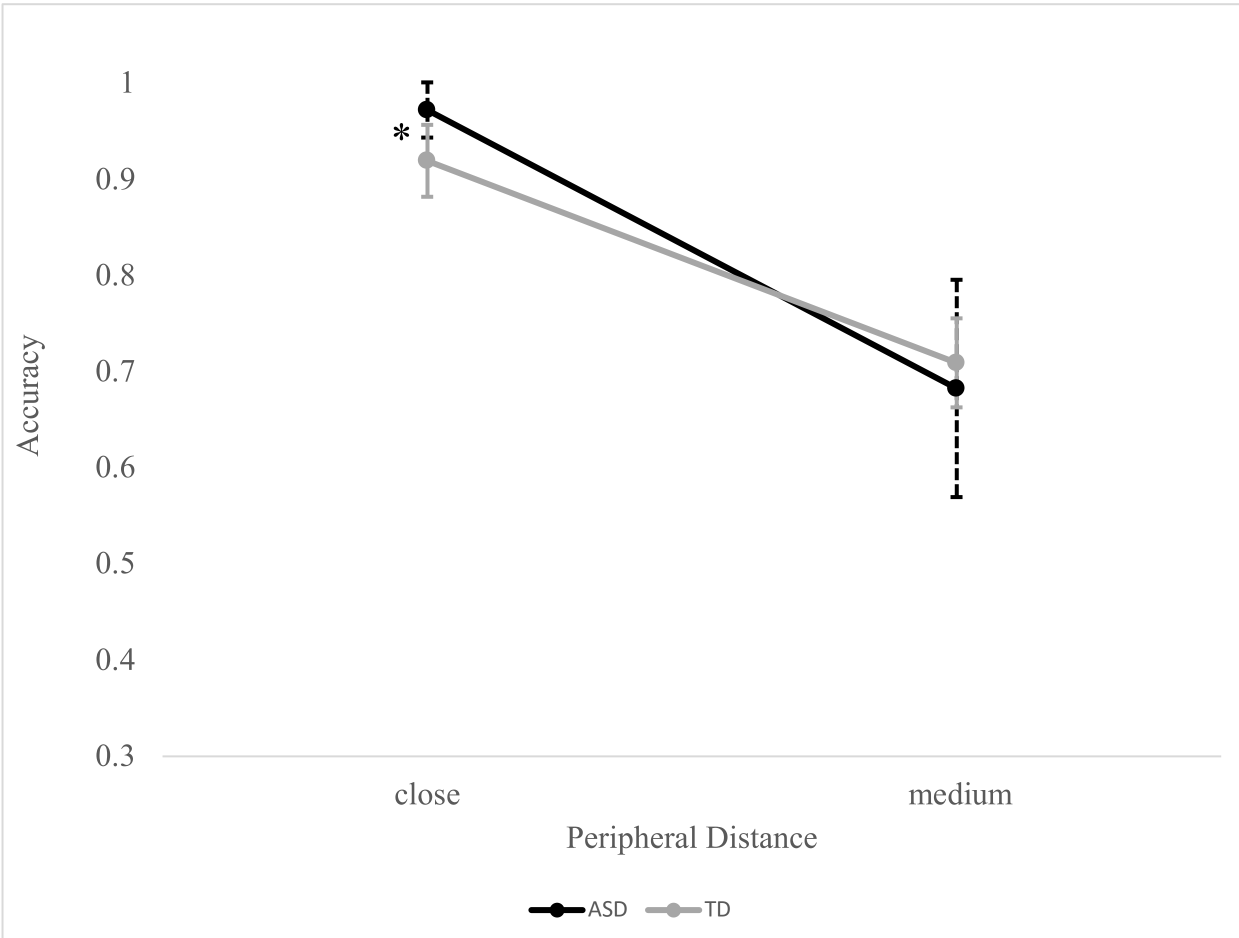
Accuracy by Distance Scores at 117ms Presentation Rate



Note. Error bars reflect 95% Confidence Intervals.

Figure 6

Accuracy by Distance Scores at 195ms Presentation Rate

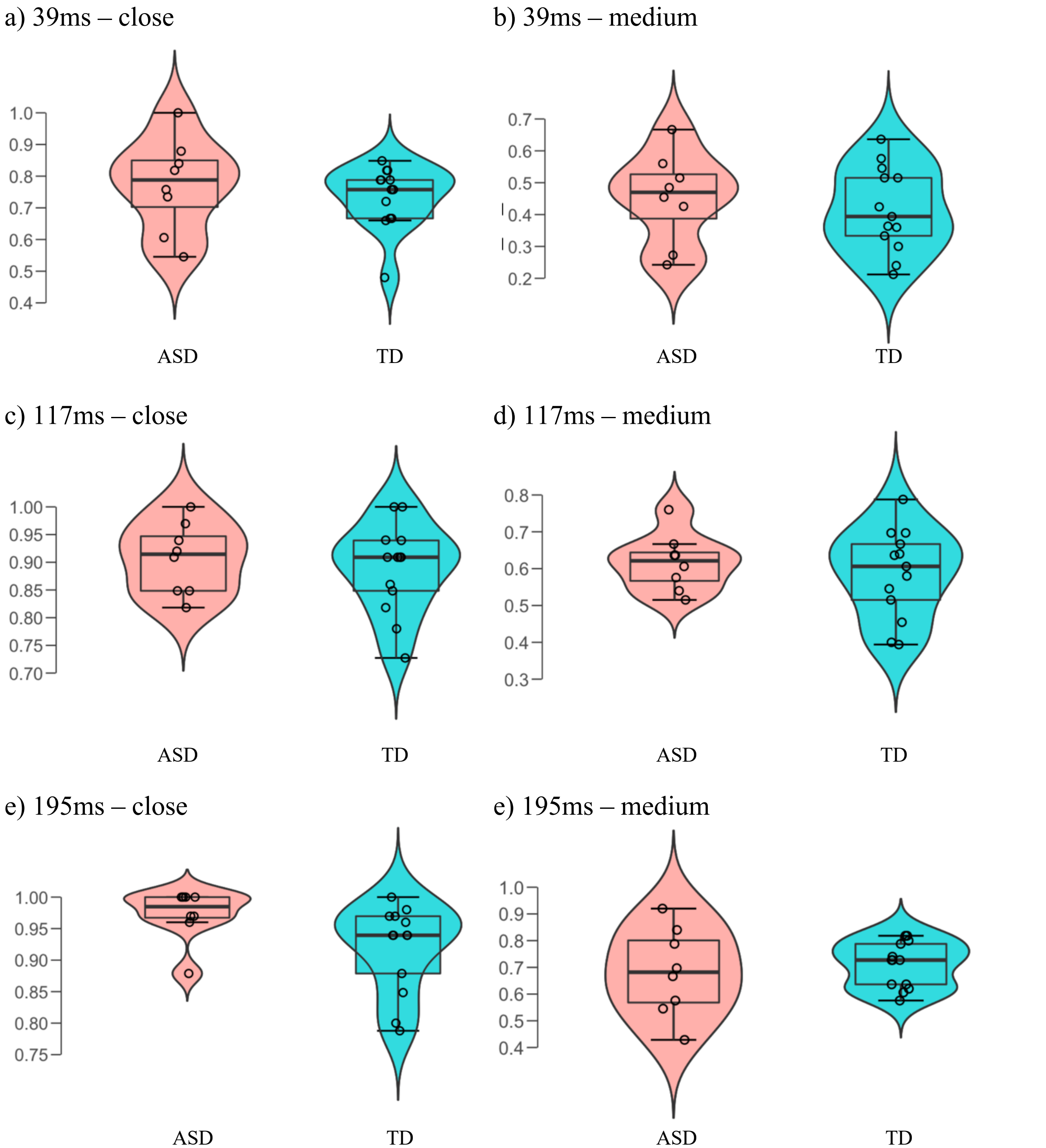


Note. Error bars reflect 95% Confidence Intervals.

* $p < 0.05$

Figure 7

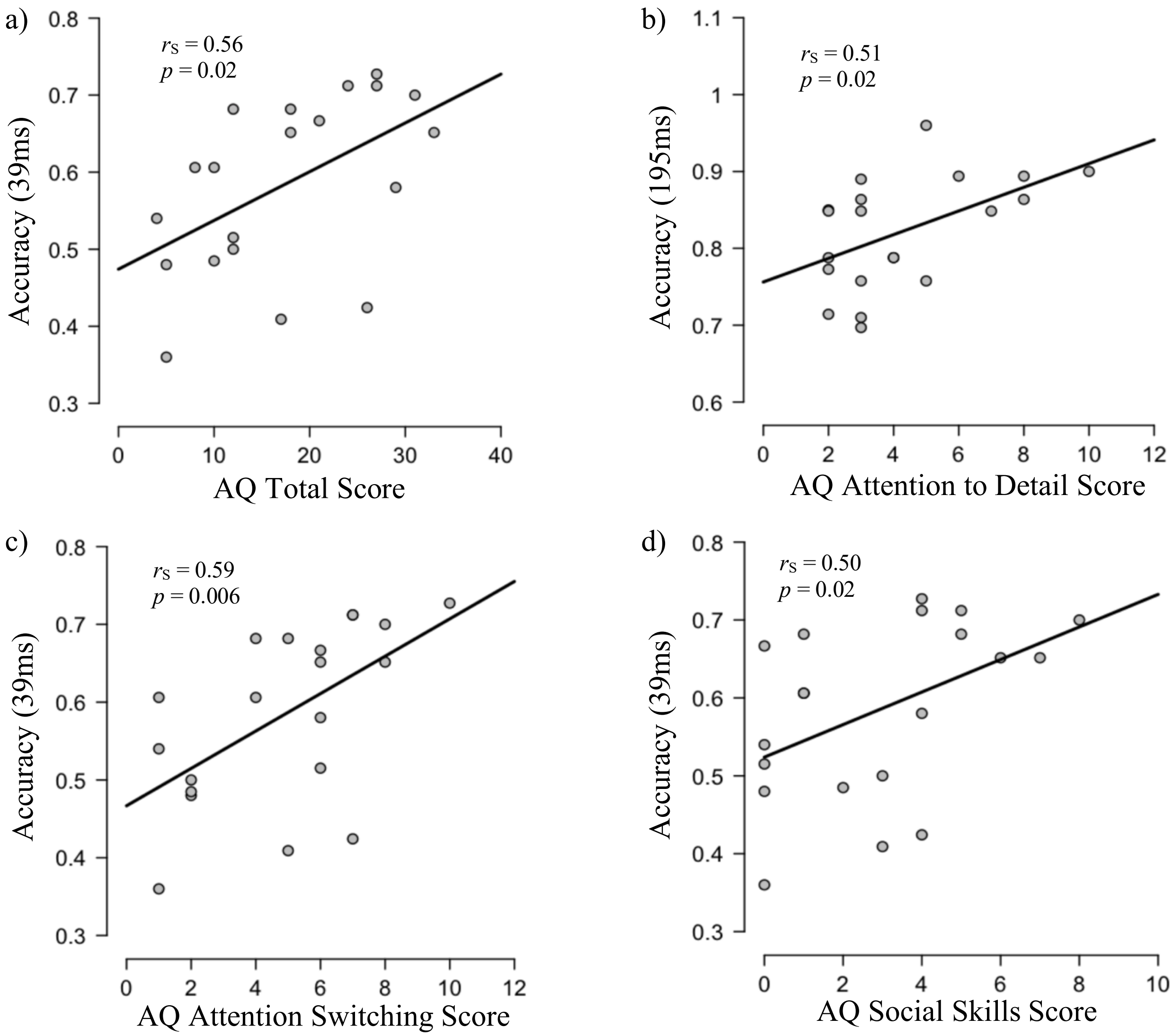
Boxplots of Accuracy Data

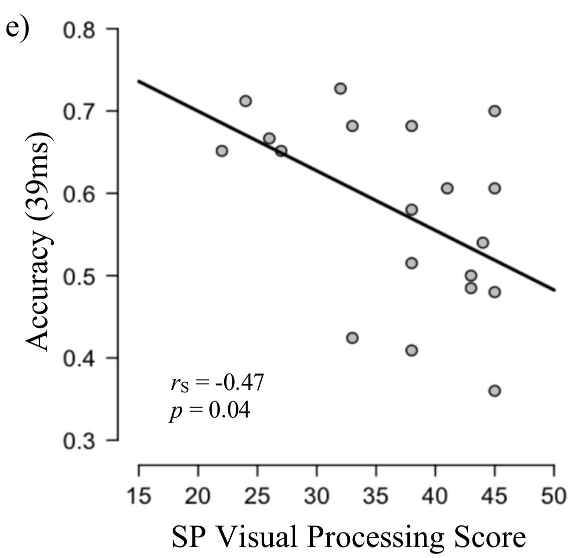


Note. Boxplots depict the distribution of accuracy scores in the ASD (red) and TD (blue) groups separately at each presentation rate (39ms, 117ms, 195ms) by distance (close, medium) manipulation.

Figure 8

Plots of Significant Correlations





Note. All plots depict Spearman correlations across both ASD and TD groups; r_S = Spearman's rho.

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