Pathways of Perceptual Primacy: ERP Evidence for Relationships Between Autism Traits and
Enhanced Perceptual Functioning

Elizabeth A. Kaplan-Kahn, Aesoon Park, Natalie Russo*

Department of Psychology, Syracuse University, Syracuse, NY United States of America

* Corresponding author:

Email: nrusso@syr.edu

Address: 403 Huntington Hall, Department of Psychology, Syracuse University Syracuse, NY
13244

Abstract

Autistic individuals show enhanced perceptual functioning on many behavioral tasks. Neurophysiological evidence also supports the conclusion that autistic individuals utilize perceptual processes to a greater extent than neurotypical comparisons to support problem solving and reasoning; however, how atypicalities in early perceptual processing influence subsequent cognitive processes remains to be elucidated. The goals of the present study were to test the relationship between early perceptual and subsequent cognitive event related potentials (ERPs) and their relationship to levels of autism traits. 62 neurotypical adults completed the Autism Spectrum Quotient (AQ) and participated in an ERP task. Path models were compared to test causal relationships among an early perceptual ERP (the P1 component), a subsequent cognitive ERP (the N400 effect), and the Attention to Detail subscale of the AQ. The size of participants' P1 components was positively correlated with the size of their N400 effect and their Attention to Detail score. Model comparisons supported the model specifying that variation in Attention to Detail scores predicted meaningful differences in participants' ERP waveforms. The relationship between Attention to Detail scores and the size of the N400 effect was significantly mediated by the size of the P1 effect. This study revealed that neurotypical adults with higher levels of Attention to Detail show larger P1 differences, which, in turn, correspond to larger N400 effects. Findings support the Enhanced Perceptual Functioning model of autism, suggesting that early perceptual processing differences may cascade forward and result in modifications to later cognitive mechanisms.

Keywords: ERP, Path analysis, P1, N400, Autism traits

1. Introduction

Autism is a neurodevelopmental condition defined by deficits in social communication and the presence of restricted or repetitive patterns of behavior, interests, or activities (American Psychiatric Association, 2013). For decades, there has been significant focus on the wide variety of social communication deficits in autism, including impaired social interactions (e.g., Carter, Davis, Klin, & Volkmar, 2005), deficits in theory of mind (e.g., Baron-Cohen, Leslie, & Frith, 1985), decreased eye contact (e.g., Senju & Johnson, 2009), and delays in language acquisition (e.g., Landry & Loveland, 1988). As reflected by this extensive body of research, social communication deficits have historically been viewed as the primary feature of autism, while additional characteristics, such as atypical perceptual processing, have been conceptualized as a secondary consequence. However, in recent years, a renewed interest in the atypical perceptual features of autism has manifested in increasing amounts of research. The way in which basic perceptual information about the world is taken in and processed creates and colors the realities in which we live; as information cascades from low-level perceptual features to higher-level cognitive mechanisms, small diversions in such processing streams can result in substantial cognitive and behavioral differences. Hence, a deeper understanding of how these perceptual functions are atypical in autism may provide insight into the worldview of individuals on the spectrum.

One theoretical framework put forth to explain the perceptual differences in autism is the Enhanced Perceptual Functioning (EPF) model (Mottron et al., 2006; Mottron and Burack, 2001). The primary claim of EPF theory posits that processing mechanisms dedicated to the detection, discrimination, and categorization of perceptual stimuli are enhanced among autistic persons. The enhancement of these lower-level processes causes the weighting of perceptual

information to be superior to that of higher-order cognitive operations, leading to enhanced perception of basic sensory information. This is not to say that higher-order cognitive mechanisms are deficient in autistic individuals, but rather, that such mechanisms are optional, while they are mandatory among neurotypicals (Mottron et al., 2006). Over the course of development, the increased weighting of perceptual over cognitive processes in autism leads to a superior performance on a variety of perceptual tasks (Mottron et al., 2013, 2009).

The EPF model is positioned on robust empirical evidence documenting superior autistic perceptual skills in across nearly all sensory modalities. The domain of vision is the most widely studied arena of enhanced perception in autism (Dakin and Frith, 2005; Kaldy et al., 2016; Simmons et al., 2009). Autistic individuals are faster at identifying targets in embedded figure tasks (Jarrold et al., 2005; Jolliffe and Baron-Cohen, 1997; Shah and Frith, 1983), as well as featural (Kemner et al., 2008) and conjunctive (O’Riordan, 2004) visual search tasks. Enhanced autistic performance on visual search tasks is evidenced early in development; adolescents (Joseph et al., 2009), children (Plaisted et al., 1998), and toddlers (Kaldy et al., 2011) on the autism spectrum are faster in visual search tasks than age-matched controls. High-risk infants who later receive an autism diagnosis demonstrate superior performance on visual search tasks at 9 and 15 months of age as compared to high-risk infants who did not receive an autism diagnosis. Further, superior performance on the infant visual search task specifically predicts autism traits, but not ADHD or anxiety symptoms, at 3-years of age (Cheung et al., 2018). Such early differences in visual search tasks underscore the assumption that differences in perceptual processing are not secondary consequences of atypical social development, but rather a primary feature of autism.

In addition to superior behavioral performance on visual tasks in autistic individuals, an increasing body of neuropsychological research highlights brain-behavior relationships that support EPF model. Neuropsychological studies are crucial compliments to behavioral paradigms because they investigate how psychological mechanisms unfold over time (Banaschewski and Brandeis, 2007) and are substantiated at a neuronal level in the brain (Aue et al., 2009). Functional magnetic resonance imaging (fMRI) investigations have yielded strikingly consistent results. On a host of perceptual reasoning tasks, including embedded figure (Damarla et al., 2010; Lee et al., 2007; Manjaly et al., 2007), matrix reasoning (Soulières et al., 2009), block design (Bölte et al., 2008), and visual search tasks (Keehn et al., 2008), autistic participants exhibit decreased prefrontal cortex activation and increased activation in visual cortex regions compared to neurotypical comparison groups. The findings of these individual fMRI studies were reiterated in an Activation Likelihood Estimation meta-analysis (Samson et al., 2012), providing strong physiological evidence that persons on the spectrum utilize perceptual processes to a greater degree than neurotypical individuals in reasoning and problem solving.

Despite robust behavioral and neuropsychological evidence for enhanced perceptual functioning among autistic individuals, the cognitive consequences of such early perceptual processing differences remain unclear. It is plausible that atypicalities at the initial stages of information processing cascade forward into subsequent cognitive mechanisms. Electrophysiology and event related potentials (ERPs) are methods particularly suited to answering questions regarding how early perceptual processing atypicalities may affect subsequent cognitive mechanisms. Further, examining how processes unfold over time provides

additional insights that may be masked by typical behavioral performance (Banaschewski & Brandeis, 2007).

For instance, autistic individuals show decreased N400 effects to semantically incongruous stimuli as compared to neurotypical individuals (Dunn & Bates, 2005; Dunn, Vaughan, Kreuzer, & Kurtzberg, 1999; Fishman, Yam, Bellugi, Lincoln, & Mills, 2011; Pijnacker, Geurts, van Lambalgen, Buitelaar, & Hagoort, 2010; Strandburg et al., 1993). The N400 effect is a negative deflection in the ERP waveform that is larger when stimulus information is unexpected or incongruent with the preceding context, and decades of research have supported the N400 effect as a robust indicator of semantic processing (Kutas and Federmeier, 2011; Kutas and Hillyard, 1984, 1980). Many have interpreted decreased N400 effects in autism to be indicative of deficits in semantic processing; however, behavioral accuracy on these tasks are comparable across autistic and neurotypical groups, leaving open the question of *how* autistic individuals are solving such tasks.

Russo and colleagues shed light on this question by examining the full ERP time window, rather than only where N400 effects typically occur. Findings demonstrated that while autistic adolescents exhibited reduced N400 effects as compared to matched neurotypical participants on a semantic violation paradigm (replicating previous findings), the autistic participants showed *earlier* discrimination between congruent and incongruent trials (Russo et al., 2012). Specifically, autistic participants exhibited a significant difference between conditions in occipital regions during the P1 time window. The P1 component is an obligatory ERP response to exogenous stimuli which typically occurs between 50 – 150 ms after the onset of a stimulus and is largest in occipital regions (Luck, 2014). Critically, the P1 reflects perceptual processing, as opposed to cognitive processing (Doniger et al., 2000). The ERP results of Russo

et al. (2012) complement fMRI evidence, indicating that persons on the spectrum recruit different areas of cortex, specifically regions dedicated to perceptual processing, when engaging in tasks for which neurotypical participants typically utilize prefrontal regions dedicated to cognitive processes. In sum, it appears that even when behavioral performance is similar across groups, autistic participants rely on early perceptual processes to arrive at the same behavioral outcomes as neurotypical participants using cognitive strategies.

The goal of our study was to expand of the results of Russo et al.'s 2012 study in two ways. First, we examined the relationship between the P1 and N400 components in a group of neurotypical adults. Though Russo et al. (2012) did not find statistically significant differences between conditions in the P1 time window for their neurotypical participants, the relationship between the size of the P1 and N400 effects was not explored, leaving open questions about if and how early perceptual processes, reflected in ERPs, are related to subsequent cognitive processing. Second, in order to connect ERP indicators of processing to levels of autism traits, we assessed whether the size of participants' P1 and N400 effects were related to participants' self-reported levels of Attention to Detail as measured by the Autism Spectrum Quotient (AQ; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001). The Attention to Detail subscale was specifically selected because the P1 component is a sensitive index of attention (Heinze, Luck, Mangun, & Hillyard, 1990; Luck, Heinze, Mangun, & Hillyard, 1990), and attention to detail is a trait commonly described in autism (Baron-Cohen et al., 2009). The subscale was particularly relevant for the current study as participants were asked to respond quickly as to whether the audio and visual stimuli were congruent or incongruent. Further, the task was not social, did not involve any aspect of language or communication, and did not require imaginative thought or any explicit modulation of attention. Unidirectional causal relationships between the

ERP components and self-reported levels of attention to detail were examined using path analysis models.

2. Methods

2.1 Participants

62 monolingual adults (28 female) between the ages of 18 and 23 years participated in the study. Participants were recruited through the undergraduate psychology research pool. Exclusion criteria included any history of hearing disorder, seizures, or any other neurological disorders. Participants received course credit for participating in the study. Each participant signed an informed consent form before participating. All consent forms and testing procedures were approved by the university's Institutional Review Board prior to use.

2.2 Experimental Task

Modeling our task off of the paradigm used in Russo et al. (2012), participants watched a screen while pictures of animals were presented simultaneously with an animal sound. Pictures included images of a dog and a frog, and audio included sound clips of a dog bark and a frog ribbit. Stimuli were presented simultaneously at a rate of 250 ms per trial. On congruent trials (50% of trials), the animal picture and audio matched (i.e., a dog picture presented with a bark and a frog picture presented with a ribbit). On incongruent trials (50% of trials), the animal picture and audio were mismatched (i.e., a dog picture presented with a ribbit and a frog picture presented with a bark). Participants responded with a key press whether the trial was congruent or incongruent. Response keys were displaced vertically in the middle of the keyboard to minimize the effect of response side on the ERP waveforms. Trials were presented in two blocks of 750 randomized trials (375 congruent trials and 375 incongruent trials in each). Participants' EEG activity was recorded during the experimental task.

2.3 EEG Recording and ERP Processing

EEG was recorded continuously at 1024 Hz using Net Station Software (EGI; Electrical Geodesics, 2003). Electrodes were referenced on-line to the Cz electrode, and impedances were kept below 50 k Ω . Subsequent EEG data were analyzed using EEGLAB (Delorme and Makeig, 2004), and ERPLAB (Lopez-Calderon and Luck, 2014) software. The off-line EEG data were band pass filtered (.01 – 30Hz) and re-referenced to the average of the mastoids. ERPs were time-locked to the onset of the audiovisual stimuli, and the epoch time-window was -100 ms – 700 ms post-onset (baseline window: -100 to 0 ms). Following baseline correction, a moving peak-to-peak window operation was used to identify and remove epochs containing artifacts.

2.4 Measure of Autism Traits

Participants were administered the AQ (Baron-Cohen et al., 2001). The measure produces five subscales – Social Skills, Attention Switching, Attention to Detail, Communication, and Imagination – and an overall total score. For the purpose of the present study, only the Attention to Detail subscale was used because the experimental task did not involve any social, communication or imaginative components, nor did it assess executive functioning. Items on the AQ are scored dichotomously, with higher scores indicating a greater degree of autism traits. Based on the original sample of 1,088 participants with and without autism, the Attention to Detail subscale of the AQ demonstrated moderate internal consistency (Cronbach's $\alpha = 0.63$) and sufficient test-retest reliability (Baron-Cohen et al., 2001). Autism traits are normally distributed amongst the population (Constantino and Todd, 2003; Posserud et al., 2006; Ruzich et al., 2015), and scores on the AQ and its component subscales are approximately continuous and normally distributed amongst the general population (Baron-Cohen et al., 2001), justifying the use of the AQ in the current sample of participants.

2.5 Path Analysis

Path analyses were conducted using *Mplus* (Muthén and Muthén, 2017), a structural equation modeling software, to test the two alternative path models' fit to the data. Path analysis was beneficial for the current study because it allowed for the modeling of causal relationships between sets of predictor, mediator, and outcome variables simultaneously in a single model. As such, it was a more efficient way of modeling the hypothesized mediation relationships than a traditional mediation test using multiple regression (Jihye Jeon, 2015).

Significance testing for the mediating effects in each model was conducted by a Sobel first-order test (Sobel, 1982) using the *Mplus* Model Indirect command. The significance tests of mediation were complemented with estimates of 95% bias-corrected bootstrap confidence intervals of the mediating effect based on 20,000 bias-corrected bootstrap resamples. Bootstrapped confidence intervals which do not contain zero indicate significant mediation. The bias-corrected bootstrap method of mediation estimation requires smaller sample sizes to attain better power than a Sobel first-order test and Baron & Kenny's (1986) tests for many conditions (Fritz and MacKinnon, 2007). Additionally, bias-corrected bootstrap methods provide the most statistical power as compared to other resampling methods, such as Jackknife (Mosteller and Tukey, 1977), Monte Carlo, or percentile bootstrap (Efron and Tibshirani, 1993) methods (MacKinnon et al., 2004). The proportion of the total effect that was mediated by the mediating variable was used as an additional effect size measure (MacKinnon, 2008).

Non-nested model comparisons for the two models were based on the Akaike Information Criterion (AIC) and sample-size adjusted the Bayesian Information Criterion (BIC). A 10-point difference in AIC and sample-size adjusted BIC is evidence of a model difference in

goodness of fit, favoring the model with the smaller AIC and sample size-adjusted BIC values (Burnham and Anderson, 2004).

3. Results

3.1 Descriptive Analyses

Descriptive analyses were conducted with *R*, Version 1.1.463 (R Development Core Team, 2019). Means, standard deviations, and bi-variate correlations between study variables are presented in Table 1. All study variables were continuous and normally distributed (skewness = -0.53 to 0.87; kurtosis = -1.95 to 1.12), justifying the use of maximum likelihood (ML) estimation in the subsequent path analyses

Table 1.

Means (and Standard Deviations) of Study Variables and Their Bivariate Correlation Coefficients

Variable (range)	<i>M</i> (<i>SD</i>)	<i>r</i>			
		1.	2.	3.	4.
1. Male Sex (0 = Female; 1 = Male)	0.55(0.50)	--			
2. Age (18.10 – 22.60)	19.25 (1.13)	0.01	--		
3. Mean P1 Amplitude Difference (-0.74 – 1.69)	0.12 (0.54)	-0.01	0.06	--	
4. Mean N400 Amplitude Difference (-3.56 – 3.49)	0.71 (1.58)	0.04	-0.09	0.28*	--
5. AQ Attention to Detail Score (0 – 9)	4.41 (2.31)	0.05	0.04	0.31*	0.14

Note. N = 56, due to missing data.

*p < 0.05

3.2 ERP Analyses

3.2.1 P1 Analysis

P1 scalp distributions are maximal over the occipital lobe, and the experimental stimuli were presented in the center of the screen, avoiding any lateralization of the P1 responses (Luck, 2014; Luck & Kappenman, 2012). Thus, we *a priori* selected the Oz electrode (E75), a midline electrode located at the back of the occipital lobe, to analyze visual P1 responses (Figure 1). To select an unbiased time window to analyze P1 responses, a grand-average waveform was created by averaging ERP responses across condition. Based on the times when the grand-average

waveform crossed the zero-voltage axis, the P1 time window was selected to be 50 – 120 ms.

Mean amplitudes for P1 responses were determined by calculating the average voltage within the P1 time window.

Figure 1. ERP waveform at the Oz (E75) electrode, used for P1 analysis

Mean P1 amplitudes were submitted to a repeated measures analysis of variance (RM-ANOVA) with the within-subject factors of block (block 1, block 2) and congruency (congruent, incongruent) using Greenhouse-Geisser corrections to correct violations of sphericity. The RM-ANOVA revealed no main effects of block ($F(1, 45) = 3.07, p = .09, \eta^2_G = .002$), nor congruency ($F(1, 45) = 1.861, p = .18, \eta^2_G = .002$), nor an interaction between factors ($F(1, 45) = 0.05, p = .83, \eta^2_G < .0001$).

3.2.2 N400 Analysis

N400 scalp distributions vary depending on the experimental task (Kutas and Federmeier, 2011), but have been previously reported to occur in the fronto-central regions for similar tasks

(Russo et al., 2012). We *a priori* selected the FCz electrode (E6), a midline electrode located at the frontal lobe, to analyze N400 responses (Figure 2). Based on published guidelines (Duncan et al., 2009; Kutas and Federmeier, 2011), the N400 time window was set *a priori* at 300 – 500 ms. Mean amplitudes for N400 responses were determined by calculating the average voltage within the N400 time window.

Figure 2. ERP waveform at the FCz (E6) electrode, used for N400 analysis

Mean N400 amplitudes were submitted to a RM-ANOVA with the within-subject factors of block (block 1, block 2) and congruency (congruent, incongruent), using Greenhouse-Geisser correction. Although the RM-ANOVA revealed no main effect of block ($F(1, 45) = 0.18, p = .68, \eta^2_G = .0002$), nor an interaction between factors ($F(1, 45) = 0.01, p = .93, \eta^2_G < .0001$), a significant main effect of congruency was observed ($F(1, 45) = 11.07, p = .002, \eta^2_G = .005$), suggesting the presence of a typical N400 effect.

3.3 Relationship between ERP components and AQ

ERP difference waves were created to test whether the size of participant's P1 components to congruent and incongruent trials was related to the subsequent size of their N400 effect. The size of the P1 effect was operationalized as the difference in the mean amplitudes of the P1 waves to congruent and incongruent trials within the time window of 50 – 120 ms (i.e., congruent – incongruent). Similarly, the size of the N400 effect was operationalized in a single variable by subtracting the mean amplitude of the N400 wave to incongruent trials from the mean amplitude of congruent trials.

The size of the P1 difference wave was significantly correlated with the size of N400 effect ($r = 0.28, p = .03$). The positive correlation indicates that participants who showed larger differences between conditions in the P1 time window showed larger differences between conditions in their N400 effects. The size of participants' P1 difference waves were positively correlated with their Attention to Detail score ($r = 0.31, p = .02$), revealing that participants who rated themselves as having higher levels of Attention to Detail showed larger differences in their early perceptual ERP waveforms to congruent and incongruent trials. Interestingly, although variables both were related to the size of the P1 difference wave, Attention to Detail scores were not significantly correlated with the size of the N400 difference wave ($r = 0.14, p = .29$).

To further visualize the relationship between self-reported levels of Attention to Detail and ERP components, we examined the ERP waves for participants in the bottom and top quartiles of the Attention to Detail score distribution. Participants ($n = 11$) whose self-reported levels of Attention to Detail fell at or below a 2 on the AQ subscale (range = 0 – 9) were classified as falling in the lowest quartile. Participants ($n = 13$) whose self-reported levels of Attention to Detail fell at or above a 7 were classified as falling in the top quartile. The ERP waveforms (Figure 3) corroborate the statistical correlations presented above. The difference in

the P1 waveforms appears larger for the participants who fell in the top quarter of Attention to Detail scores (Figure 3, panel D) than for the participants who fell in the lowest quartile (Figure 3, panel B). Similarly, participants who scored in the top quartile of AQ Attention to Detail scores appear to have a much larger N400 effect (Figure 3, panel C) than participants who scored in the lowest quartile (Figure 3, panel A).

Figure 3. ERP figures for participants with Attention to Detail scores in the lowest quartile (top panels; A. and B.) and highest quartile (bottom panels; C. and D.). The N400 effect was analyzed at the FCz (E6) electrode (left panels; A. and C.) and the P1 component was analyzed at the Oz (E75) electrode (right panels; B and D.).

3.4 Path Analysis

3.4.1 Model 1

In Model 1, the size of the P1 effect, was entered as the predictor variable. The size of the N400 effect was entered as the mediator variable. The outcome variable was attention to detail

trait levels. Explained variance of the outcome variable (Attention to Detail scores) and standardized path coefficients (with standard errors in parentheses) for Model 1 are presented in Figure 4. The effects of participant sex and age on the mediating and outcome variables were controlled for (paths not shown in figure for simplicity). In regard to the indirect path from the predictor to the mediating variable, the size of the P1 difference wave was significantly associated with the size of the N400 difference wave (path a; $b = 0.85$, $SE = 0.36$, $\beta = 0.23$, $p = .03$). In regard to the indirect path from the mediating variable to the outcome variable, the size of the N400 difference wave was not significantly associated with participants' self-reported level of Attention to Detail on the AQ (path b; $b = 0.09$, $SE = 0.16$, $\beta = 0.06$, $p = .54$). For the direct path from the predictor variable to the outcome variable, the size of the P1 difference wave was significantly associated with participants' self-reported level of Attention to Detail on the AQ (path c'; $b = 1.23$, $SE = 0.59$, $\beta = 0.29$, $p = .04$). No significant mediation effect was indicated by either the Sobel first-order test ($b = 0.08$, $SE = 0.15$, $\beta = 0.02$, $p = .61$), or the bias-corrected bootstrapped confidence interval (95% bias-corrected bootstrapped CI [-0.118, 0.577]). Only 6% of the total effect of the size of the P1 difference wave on participants' self-reported level of Attention to Detail was mediated by the size of the N400 difference wave.

Figure 4. Standardized path coefficients (and standard errors) of Model 1. The effects of sex and age on the mediator and outcome would be controlled for (paths not shown). $N = 56$.

3.4.2 Model 2

Given that there was no strong theoretical justification for why the ERP waves would unidirectionally predict self-report scores on the AQ, an alternative path model was tested. That is, in Model 2, Attention to Detail was entered as the predictor variable; the size of the P1 effect was entered as the mediator variable, and the size of the N400 was entered as the outcome variable. Effects of participant sex and age on the mediation and outcome variable were controlled for in both models.

Explained variance of the outcome variable (size of the N400 difference wave) and standardized path coefficients (with standard errors in parentheses) for Model 2 are presented in Figure 5. The effect of participant sex and age on the mediating and outcome variables were controlled for (paths not shown in figure for simplicity). In regard to the indirect path from the predictor to the mediating variable, participants' self-reported level of Attention to Detail was significantly associated with size of the P1 difference wave (path a; $b = 0.07$, $SE = 0.04$, $\beta = 0.31$, $p = .04$). In regard to the indirect path from the mediating variable to the outcome variable, the size of the P1 difference wave was significantly associated with the size of the N400 difference wave (path b; $b = 0.79$, $SE = 0.37$, $\beta = 0.27$, $p = .04$). In regard to the direct path from the predictor variable to the outcome variable, participants' self-reported level of Attention to Detail was not associated with the size of the N400 difference wave (path c'; $b = 0.04$, $SE = 0.07$, $\beta = 0.06$, $p = .54$). Significant mediation was not indicated by the Sobel first-order test ($b = 0.06$, $SE = 0.04$, $\beta = 0.08$, $p = .19$); however, the bias-corrected bootstrapped confidence interval

for the overall indirect effect did not contain zero, indicating a significant mediation effect (95% bias-corrected bootstrapped CI [0.001, 0.267]). Further, as an effect size measure of the mediating effect, 57% of the total effect of participants' self-reported level of Attention to Detail on the size of the N400 difference wave was mediated by the size of the P1 difference wave.

Figure 5. Standardized path coefficients (and standard errors) of Model 2. The effects of sex and age on the mediator and outcome would be controlled for (paths not shown). N = 56.

3.4.3 Model Comparison

Model comparisons revealed that Model 1 (AIC = 470.87; S.I. BIC = 458.58) had poorer model fit values than Model 2 (AIC = 308.71; S.A. BIC = 296.42). In other words, Model 2 resulted in smaller AIC ($\Delta\text{AIC} = 162.15$) and sample size-adjusted BIC ($\Delta\text{BIC} = 162.16$) values, indicating a significantly better fit to the data compared to Model 1.

4. Discussion

Our study aimed to examine the relationships between early perceptual and subsequent cognitive ERPs in neurotypical adults and test how participants' level of attention to detail was related to the size of their ERPs. The grand-averaged ERP waveforms replicated previous

findings of semantic violation paradigms in neurotypical populations: there were no statistically significant differences between congruent and incongruent conditions in the P1 time window, but there was a significant N400 effect in the expected 300 – 500 ms time period. These results replicate the findings of the adolescent neurotypical sample in Russo et al. (2012) and validate the use of our semantic violation paradigm. Even at the quick presentation rate, the current sample of neurotypical adults showed larger ERP negativity to incongruent conditions (i.e., a barking frog) than congruent conditions (i.e., a barking dog) during the N400 time window.

Russo et al. (2012) found that neurotypical adolescents exhibited an effect of condition (i.e., significant differences in the ERP waveforms to congruent and incongruent conditions) in the typical N400 time window and not in the earlier P1 time window. The pattern was reversed for the sample of autistic adolescents: adolescents on the spectrum exhibited a significant condition effect in the *earlier* P1 time window and not in the typical N400 time window. Based on the results of Russo et al. (2012), one possible outcome of the current data might have been an inverse relationship between the P1 effect size and N400 effect size. In other words, participants who exhibited *increased* condition discrimination in early perceptual time windows would show *decreased* condition discrimination at later time windows. Our data, however, revealed a positive correlation between the P1 and N400 effect sizes. Participants who displayed larger differences between congruent and incongruent their P1 waveforms exhibited larger N400 effects.

The data support several possible explanations for the relationship between perceptual and cognitive processes among neurotypical adults. First, the size of the P1 wave is modulated by selective attention (Hillyard, Vogel, Luck, & Anllo-Vento, 1998; Luck, Woodman, & Vogel, 2000); thus, it is possible that small early differences in P1 amplitude to congruent and incongruent trials may have been driven by variability of selective attention deployment. This

explanation, however, is unlikely as congruent and incongruent trials were presented randomly and participants could not predict ahead of the trial which condition they would see.

A second explanation posits that neurotypical individuals who notice the difference between congruent and incongruent conditions at the perceptual level benefit from this slight distinction and feed this enhanced discrimination forward to their semantic networks, resulting in larger N400 effects. This explanation is consistent with EPF theory in that neurotypical individuals are more likely to rely on higher-order cognitive processes than autistic individuals; thus, it is plausible that for neurotypical adults, enhanced perceptual discrimination leads to enhanced semantic discrimination. This pattern likely results from strong associations between early perceptual and later cognitive processes for neurotypical individuals – over the course of developmental time neurotypical individuals build patterns of association and activation in their processing networks, and those processes are strengthened through the repeated use. According to the EPF theory, this pattern of processing would differ in autism: autistic individuals are more likely to utilize their superior perceptual processing and are less likely to feed such information forward to higher-order processes, such as semantic networks. Though this hypothesis is not tested in the current study, it is an exciting avenue for future research to pursue.

Understanding the relationship between P1 and N400 effect sizes is complimented and deepened through exploring how the size of these ERP components relates to levels of autism traits. Our data revealed that participants with higher self-reported levels of attention to detail were more likely to show larger P1 effects, suggesting that individuals who identified with higher levels of attention to detail exhibited greater distinctions between congruent and incongruent trials in the early perceptual time window. This finding is consistent with the EPF theory in that neurotypical individuals with higher levels of autism traits were more likely to

demonstrate enhanced perceptual discrimination. Interestingly, although the size of participants' P1 effect was positively correlated with their N400 effect size, the relationship between participants attention to detail and N400 effect size was not significant. The relationship between these three variables is best understood through parsimonious path models, which confer the benefit of testing unidirectional causal relationships between variables.

Model 1 predicted that the relationship between participants' early perceptual ERPs and their self-reported scores of Attention to Detail on the AQ would be mediated by participants' late perceptual ERPs. The first mediation model was compared to Model 2, which predicted that the relationship between participants' self-reported scores of Attention to Detail on the AQ and the size of the N400 effect would be mediated by the size of the P1 effect. Model 2 demonstrated significantly better model fit indices than Model 1, and was thus determined to be a better model of the data.

The results of Model 2 indicate that the relationship between participants' levels of Attention to Detail and the size of their N400 effect was significantly mediated by the size of their P1 effect. The presence of a significant mediating effect was also supported by the test of joint significance (Cohen and Cohen, 1983). The test of joint significance is a variant of the classic component steps to determine causal relationships between predictor, mediator, and outcome variables (Baron and Kenny, 1986) in that it does not require the initial causal step of a significant correlation between the causal and outcome variables (Kenny et al., 1998; Mallinckrodt et al., 2006). In Model 2, the indirect path from participants' self-reported Attention to Detail score on the AQ (predictor) to the size of their P1 difference wave (mediator) *and* indirect path from the size of the P1 difference wave (mediator) to the size of the N400 difference wave (outcome) were both significant, fulfilling both requirements of the test of joint

significance. The test of joint significance exhibits a satisfactory balance of statistical power and Type I error (MacKinnon et al., 2002).

One limitation of the present study is that participants included only a sample of neurotypical adults. Although there is evidence to suggest that autism traits, including attention to detail, are normally distributed among the typically developing population (Hurst et al., 2007; Ruzich et al., 2015), examining correlations between AQ scores and other measures may be impacted by a constricted range of scores on the AQ. Future research can extend and strengthen the present findings by including participants on the autism spectrum. Additionally, future research may extend the current study by exploring the relationships between early perceptual and late cognitive ERPs and their relationship to levels of autism traits within the context of development. This can be accomplished by including younger groups of participants, both with and without autism diagnoses.

Although previous research has found differences between groups of individuals with and without autism in terms of both early perceptual and late cognitive ERPs (Russo et al., 2012), the present study is the first to demonstrate that the size of participants' early perceptual ERPs is related to the size of their later cognitive ERPs in a semantic violation task. Further, participants who rated themselves as having high levels of attention to detail exhibited greater differences in their P1 responses to congruent and incongruent stimuli. These findings lend support to the EPF model of autism (Motttron et al., 2009, 2006), which posits that individuals with higher levels of autism traits exhibit superior perceptual processing of information. We interpret the positive relationship between P1 and N400 effect sizes among neurotypical individuals to be indicative of a strong feed-forward flow of information from perception to higher-order levels of processing. Future research should explore whether the strength of such processes is moderated by autism

diagnosis status. Further, novel findings from the present study suggest that although there may not be a significant correlation between autism traits and the N400 effect, the relationship between these two variables is significantly mediated by the size of the P1. In other words, the relationship between a person's level of autism traits and their higher-order cognitive processes is mediated by their early perceptual processing mechanisms.

Declarations

Ethics approval and consent to participate

This study was approved by the institutional review board of Syracuse University. Informed consent was obtained from all individual participants included in the study.

Acknowledgements

The authors would like to thank Dr. Nicole Shea for her help with data collection.

Availability of data and material

The datasets generated and analyzed during the current study are available in the Open Science Foundation (OSF) repository at:
[https://osf.io/twk4h/?view_only=c9b0d60349584909a81a96becee8d560].

Competing interests

The authors declare that they do not have any competing interests.

Funding

This work was supported by the Hill Collaboration for Environmental Medicine.

Author Contributions (CRediT author statement)

Elizabeth A. Kaplan-Kahn: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft. **Aesoon Park:** Methodology, Supervision, Writing – reviewing and

editing. **Natalie Russo:** Funding acquisition, Methodology, Supervision, Writing – reviewing and editing. All authors have read and approved the submitted version of the manuscript.

References

- American Psychiatric Association, 2013. Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5). American Psychiatric Association, Arlington, VA.
<https://doi.org/10.1176/appi.books.9780890425596.744053>
- Aue, T., Lavelle, L.A., Cacioppo, J.T., 2009. Great expectations: What can fMRI research tell us about psychological phenomena? *Int. J. Psychophysiol.* 73, 10–16.
<https://doi.org/10.1016/j.ijpsycho.2008.12.017>
- Banaschewski, T., Brandeis, D., 2007. Annotation: What electrical brain activity tells us about brain function that other techniques cannot tell us - A child psychiatric perspective. *J. Child Psychol. Psychiatry Allied Discip.* 48, 415–435. <https://doi.org/10.1111/j.1469-7610.2006.01681.x>
- Baron-Cohen, S., Ashwin, E., Ashwin, C., Tavassoli, T., Chakrabarti, B., 2009. Talent in autism: Hyper-systemizing, hyper-attention to detail and sensory hypersensitivity. *Philos. Trans. R. Soc. B Biol. Sci.* 364, 1377–1383. <https://doi.org/10.1098/rstb.2008.0337>
- Baron-Cohen, S., Leslie, A.M., Frith, U., 1985. Does the autistic child have a “theory of mind?” *Cognition* 21, 37–46. <https://doi.org/10.1097/00005373-196307000-00010>
- Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., Clubley, E., 2001. The Autism Spectrum Quotient: Evidence from Asperger syndrome/high functioning autism, males and females, scientists and mathematicians. *J. Autism Dev. Disord.* 31, 5–17.
<https://doi.org/10.1023/A:1005653411471>

- Baron, R.M., Kenny, D.A., 1986. The moderator–mediator variable distinction in social. *J. Pers. Soc. Psychol.* 1173–1182.
- Bölte, S., Hubl, D., Dierks, T., Holtmann, M., Poustka, F., 2008. An fMRI-study of locally oriented perception in autism: Altered early visual processing of the block design test. *J. Neural Transm.* 115, 545–552. <https://doi.org/10.1007/s00702-007-0850-1>
- Burnham, K.P., Anderson, D.R., 2004. Multimodel Inference. *Sociol. Methods Res.* 33, 261–304. <https://doi.org/10.1177/0049124104268644>
- Carter, A.S., Davis, N.O., Klin, A., Volkmar, F.R., 2005. Social development in autism, in: *Handbook of Autism and Pervasive Developmental Disorders*. pp. 312–334.
- Cheung, C.H.M., Bedford, R., Johnson, M.H., Charman, T., Baron-Cohen, S., Bolton, P., Blasi, A., Davies, K., Elsabbagh, M., Fernandes, J., Gammer, I., Green, J., Guiraud, J., Liew, M., Lloyd-Fox, S., Maris, H., O’Hara, L., Pasco, G., Pickles, A., Ribeiro, H., Salomone, E., Tucker, L., Yemane, F., 2018. Visual search performance in infants associates with later ASD diagnosis. *Dev. Cogn. Neurosci.* 29, 4–10. <https://doi.org/10.1016/j.dcn.2016.09.003>
- Cohen, J., Cohen, P., 1983. *Applied multiple regression/correlation analysis for the behavioral sciences*. Erlbaum, Hillsdale, NJ.
- Constantino, J.N., Todd, R.D., 2003. Autistic traits in the general population. *Arch. Gen. Psychiatry* 60, 524. <https://doi.org/10.1001/archpsyc.60.5.524>
- Dakin, S., Frith, U., 2005. Vagaries of visual perception in autism. *Neuron* 48, 497–507. <https://doi.org/10.1016/j.neuron.2005.10.018>
- Damarla, S.R., Keller, T.A., Kana, R.K., Cherkassky, V.L., Williams, D.L., Minshew, N.J., Just, M.A., 2010. Cortical underconnectivity coupled with preserved visuospatial cognition in autism: Evidence from an fMRI study of an embedded figures task. *Autism Res.* 3, 273–

279. <https://doi.org/10.1002/aur.153>

Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J. Neurosci. Methods* 134, 9–21.

<https://doi.org/10.1016/j.jneumeth.2003.10.009>

Doniger, G.M., Foxe, J.J., Murray, M.M., Higgins, B.A., Snodgrass, J.G., Schroeder, C.E., Javitt, D.C., 2000. Activation timecourse of ventral visual stream object-recognition areas: High density electrical mapping of perceptual closure processes. *J. Cogn. Neurosci.* 12, 615–621.

<https://doi.org/10.1162/089892900562372>

Duncan, C.C., Barry, R.J., Connolly, J.F., Fischer, C., Michie, P.T., Näätänen, R., Polich, J., Reinvang, I., Van Petten, C., 2009. Event-related potentials in clinical research: Guidelines for eliciting, recording, and quantifying mismatch negativity, P300, and N400. *Clin. Neurophysiol.* 120, 1883–1908.

<https://doi.org/10.1016/j.clinph.2009.07.045>

Dunn, M., Vaughan, H., Kreuzer, J., Kurtzberg, D., 1999. Electrophysiologic correlates of semantic classification in autistic and normal children. *Dev. Neuropsychol.* 16, 79–99.

<https://doi.org/10.1207/S15326942DN160105>

Dunn, M.A., Bates, J.C., 2005. Developmental change in neural processing of words by children with autism. *J. Autism Dev. Disord.* 35, 361–376. [https://doi.org/10.1007/s10803-005-3304-](https://doi.org/10.1007/s10803-005-3304-3)

3

Efron, B., Tibshirani, R.J., 1993. *An introduction to the bootstrap*. CRC press, New York, NY.

Electrical Geodesics Inc., 2003. *Net Station Acquisition Technical Manual*. Electrical Geodesics, Inc., Eugene, OR.

Fishman, I., Yam, A., Bellugi, U., Lincoln, A., Mills, D., 2011. Contrasting patterns of language-associated brain activity in autism and Williams syndrome. *Soc. Cogn. Affect. Neurosci.* 6,

- 630–638. <https://doi.org/10.1093/scan/nsq075>
- Fritz, M.S., MacKinnon, D.P., 2007. Required sample size to detect the mediated effect. *Psychol. Sci.* 18, 233–239.
- Heinze, H.J., Luck, S.J., Mangun, G.R., Hillyard, S.A., 1990. Visual event-related potentials index focused attention within bilateral stimulus arrays. I. Evidence for early selection. *Electroencephalogr. Clin. Neurophysiol.* 75, 511–527. [https://doi.org/10.1016/0013-4694\(90\)90138-A](https://doi.org/10.1016/0013-4694(90)90138-A)
- Hillyard, S.A., Vogel, E.K., Luck, S.J., Anllo-Vento, L., 1998. Sensory gain control (amplification) as a mechanism of selective attention. *Philos. Trans. R. Soc. London - Ser. B Biol. Sci.* 353, 1257–1270.
- Hurst, R.M., Mitchell, J.T., Kimbrel, N.A., Kwapil, T.K., Nelson-Gray, R.O., 2007. Examination of the reliability and factor structure of the Autism Spectrum Quotient (AQ) in a non-clinical sample. *Pers. Individ. Dif.* 43, 1938–1949.
- Jarrold, C., Gilchrist, I.D., Bender, A., 2005. Embedded figures detection in autism and typical development: Preliminary evidence of a double dissociation in relationships with visual search. *Dev. Sci.* 8, 344–351. <https://doi.org/10.1111/j.1467-7687.2005.00422.x>
- Jihye Jeon, 2015. The Strengths and Limitations of the Statistical Modeling of Complex Social Phenomenon: Focusing on SEM, Path Analysis, or Multiple Regression Models. *Int. J. Soc. Behav. Educ. Econ. Bus. Ind. Eng.* 9, 1634–1642.
- Jolliffe, T., Baron-Cohen, S., 1997. Are people with autism or Asperger's syndrome faster than normal in Embedded Figure Task? *J. Child Psychol. Psychiatry* 38, 527–534. <https://doi.org/10.1111/j.1469-7610.1997.tb01539.x>
- Joseph, R.M., Keehn, B., Connolly, C., Wolfe, J.M., Horowitz, T.S., 2009. Why is visual search

- superior in autism spectrum disorder? *Dev. Sci.* 12, 1083–1096.
<https://doi.org/10.1111/j.1467-7687.2009.00855.x>
- Kaldy, Z., Giserman, I., Carter, A.S., Blaser, E., 2016. The mechanisms underlying the ASD advantage in visual search. *J. Autism Dev. Disord.* 46, 1513–1527.
<https://doi.org/10.1007/s10803-013-1957-x>
- Kaldy, Z., Kraper, C., Carter, A.S., Blaser, E., 2011. Toddlers with autism spectrum disorder are more successful at visual search than typically developing toddlers. *Dev. Sci.* 14, 980–988.
<https://doi.org/10.1111/j.1467-7687.2011.01053.x> Toddlers
- Keehn, B., Brenner, L., Palmer, E., Lincoln, A.J., Müller, R.-A., 2008. Functional brain organization for visual search in ASD. *J. Int. Neuropsychol. Soc.* 14, 990–1003.
- Kemner, C., van Ewijk, L., van Engeland, H., Hooge, I., 2008. Brief report: Eye movements during visual search tasks indicate enhanced stimulus discriminability in subjects with PDD. *J. Autism Dev. Disord.* 38, 553–558. <https://doi.org/10.1007/s10803-007-0406-0>
- Kenny, D.A., Kashy, D.A., Bolger, N., 1998. Data analysis in social psychology, in: Gilbert, D.T., Fiske, S.T., Lindzey, G. (Eds.), *The Handbook of Social Psychology*. Oxford University Press, New York, NY, pp. 233–265.
- Kutas, M., Federmeier, K.D., 2011. Thirty years and counting: Finding meaning in the N400 component of the event related brain potential (ERP). *Annu. Rev. Psychol.* 62, 621–647.
<https://doi.org/10.1146/annurev.psych.093008.131123> Thirty
- Kutas, M., Hillyard, S.A., 1984. Brain potentials during reading reflect word expectancy and semantic association. *Nature* 307, 161–163. <https://doi.org/10.1038/307161a0>
- Kutas, M., Hillyard, S.A., 1980. Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science* (80-.). 207, 203–205.

- Landry, S.H., Loveland, K.A., 1988. Communication behaviors in autism and developmental language delay. *J. Child Psychol. Psychiatry* 29, 621–634.
- Lee, P.S., Foss-Feig, J., Henderson, J.G., Kenworthy, L.E., Gilotty, L., Gaillard, W.D., Vaidya, C.J., 2007. Atypical neural substrates of Embedded Figures Task performance in children with Autism Spectrum Disorder. *Neuroimage* 38, 184–193.
<https://doi.org/10.1016/j.neuroimage.2007.07.013>
- Lopez-Calderon, J., Luck, S.J., 2014. ERPLAB: An open-source toolbox for the analysis of event-related potentials. *Front. Hum. Neurosci.* 8, 213.
<https://doi.org/10.3389/fnhum.2014.00213>
- Luck, S.J., 2014. *An Introduction to the Event-Related Potential Technique*. The MIT Press, Cambridge, MA.
- Luck, S.J., Heinze, H.J., Mangun, G.R., Hillyard, S.A., 1990. Visual event-related potentials index focused attention within bilateral stimulus arrays. II. Functional dissociation of P1 and N1 components. *Electroencephalogr. Clin. Neurophysiol.* 75, 528–542.
[https://doi.org/10.1016/0013-4694\(90\)90139-B](https://doi.org/10.1016/0013-4694(90)90139-B)
- Luck, S.J., Kappenman, E.S., 2012. ERP Components and Selective Attention, in: *The Oxford Handbook of Event-Related Potential Components*. pp. 295–327.
- Luck, S.J., Woodman, G.F., Vogel, E.K., 2000. Event-related potential studies of attention. *Trends Cogn. Sci.* 4, 432–440. [https://doi.org/10.1016/S1364-6613\(00\)01545-X](https://doi.org/10.1016/S1364-6613(00)01545-X)
- MacKinnon, D.P., 2008. *Introduction to Statistical Mediation Analysis*. Multivariate Applications Series. Erlbaum, New York, NY.
- MacKinnon, D.P., Lockwood, C.M., Hoffman, J.M., West, S.G., Sheets, V., 2002. A comparison of methods to test mediation and other intervening variable effects. *Psychol Methods* 7, 83.

<https://doi.org/10.3816/CLM.2009.n.003.Novel>

MacKinnon, D.P., Lockwood, C.M., Williams, J., 2004. Multivariate Behavioral Constrained and Unconstrained Multivariate Normal Finite Mixture Modeling of Piagetian Data.

Multivariate Behav. Res. 39, 99–128. https://doi.org/10.1207/s15327906mbr3901_4

Mallinckrodt, B., Abraham, W.T., Wei, M., Russell, D.W., 2006. Advances in testing the statistical significance of mediation effects. J. Couns. Psychol. 53, 372–378.

<https://doi.org/10.1037/0022-0167.53.3.372>

Manjaly, Z.M., Bruning, N., Neufang, S., Stephan, K.E., Brieber, S., Marshall, J.C., Kamp-Becker, I., Remschmidt, H., Herpertz-Dahlmann, B., Konrad, K., Fink, G.R., 2007.

Neurophysiological correlates of relatively enhanced local visual search in autistic adolescents. Neuroimage 35, 283–291. <https://doi.org/10.1016/j.neuroimage.2006.11.036>

Mosteller, F., Tukey, J.W., 1977. Data analysis and regression: A second course in statistics. Addison-Wesley, Reading, MA.

Mottron, L., Bouvet, L., Bonnel, A., Samson, F., Burack, J.A., Dawson, M., Heaton, P., 2013.

Veridical mapping in the development of exceptional autistic abilities. Neurosci. Biobehav. Rev. 37, 209–228. <https://doi.org/10.1016/j.neubiorev.2012.11.016>

Mottron, L., Burack, J.A., 2001. Enhanced perceptual functioning in the development of autism, in: The Development of Autism: Perspectives from Theory and Research. Lawrence Erlbaum Associates, Mahwah, New Jersey, pp. 131–148.

Mottron, L., Dawson, M., Soulières, I., 2009. Enhanced perception in savant syndrome: Patterns, structure and creativity. Philos. Trans. R. Soc. B Biol. Sci. 364, 1385–1391.

<https://doi.org/10.1098/rstb.2008.0333>

Mottron, L., Dawson, M., Soulières, I., Hubert, B., Burack, J., 2006. Enhanced perceptual

- functioning in autism: An update, and eight principles of autistic perception. *J. Autism Dev. Disord.* 36, 27–43. <https://doi.org/10.1007/s10803-005-0040-7>
- Muthén, L.K., Muthén, B.O., 2017. *Mplus User's Guide*.
- O'Riordan, M.A., 2004. Superior visual search in adults with autism. *Autism* 8, 229–248. <https://doi.org/10.1177/1362361304045219>
- Pijnacker, J., Geurts, B., van Lambalgen, M., Buitelaar, J., Hagoort, P., 2010. Exceptions and anomalies: An ERP study on context sensitivity in autism. *Neuropsychologia* 48, 2940–2951. <https://doi.org/10.1016/j.neuropsychologia.2010.06.003>
- Plaisted, K., O'Riordan, M., Baron-Cohen, S., 1998. Enhanced visual search for a conjunctive target in autism: A research note enhanced visual search for a conjunctive target in autism. *J. Child Psychol. Psychiatry* 39, 777–783.
- Posserud, M.B., Lundervold, A.J., Gillberg, C., 2006. Autistic features in a total population of 7-9-year-old children assessed by the ASSQ (Autism Spectrum Screening Questionnaire). *J. Child Psychol. Psychiatry Allied Discip.* 47, 167–175. <https://doi.org/10.1111/j.1469-7610.2005.01462.x>
- R Development Core Team, 2019. *R: A language and environment for statistical computing*.
- Russo, N., Mottron, L., Burack, J.A., Jemel, B., 2012. Parameters of semantic multisensory integration depend on timing and modality order among people on the autism spectrum: Evidence from event-related potentials. *Neuropsychologia* 50, 2131–2141. <https://doi.org/10.1016/j.neuropsychologia.2012.05.003>
- Ruzich, E., Allison, C., Smith, P., Watson, P., Auyeung, B., Ring, H., Baron-Cohen, S., 2015. Measuring autistic traits in the general population: A systematic review of the Autism-Spectrum Quotient (AQ) in a nonclinical population sample of 6,900 typical adult males

- and females. *Mol. Autism* 6, 1–12. <https://doi.org/10.1186/2040-2392-6-2>
- Samson, F., Mottron, L., Soulières, I., Zeffiro, T.A., 2012. Enhanced visual functioning in autism: An ALE meta-analysis. *Hum. Brain Mapp.* 33, 1553–1581. <https://doi.org/10.1002/hbm.21307>
- Senju, A., Johnson, M.H., 2009. Atypical eye contact in autism: Models, mechanisms and development. *Neurosci. Biobehav. Rev.* 33, 1204–1214.
- Shah, A., Frith, U., 1983. An islet of ability in autistic children: A research note. *J. Child Psychol. Psychiatry* 24, 613–620.
- Simmons, D.R., Robertson, A.E., McKay, L.S., Toal, E., McAleer, P., Pollick, F.E., 2009. Vision in autism spectrum disorders. *Vision Res.* 49, 2705–2739. <https://doi.org/10.1016/j.visres.2009.08.005>
- Sobel, M.E., 1982. Asymptotic Confidence Intervals for Indirect Effects in Structural Equation Models. *Sociol. Methodol.* 13, 290–312. <https://doi.org/10.2307/270723>
- Soulières, I., Dawson, M., Samson, F., Barbeau, E.B., Sahyoun, C.P., Strangman, G.E., Zeffiro, T.A., Mottron, L., 2009. Enhanced visual processing contributes to matrix reasoning in autism. *Hum. Brain Mapp.* 30, 4082–4107. <https://doi.org/10.1002/hbm.20831>
- Strandburg, R.J., Marsh, J.T., Brown, W.S., Asarnow, R.F., Guthrie, D., Higa, J., 1993. Event-related potentials in high-functioning adult autistics: Linguistic and nonlinguistic visual information processing tasks. *Neuropsychologia* 31, 413–434. [https://doi.org/10.1016/0028-3932\(93\)90058-8](https://doi.org/10.1016/0028-3932(93)90058-8)