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Pupillary responses during a joint attention task are associated with nonverbal cognitive abilities and sub-clinical symptoms of autism

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Abstract

Measures of pupillary dilation provide a temporally sensitive, quantitative indicator of cognitive resource allocation. The current study included 39 typically developing children between 3 and 9 years of age. Children completed a free-viewing task designed to elicit gaze following, a core deficit of Autism Spectrum Disorders (ASD). Results revealed a negative association between children's pupil dilation and a standardized measure of nonverbal intelligence, suggesting that children with lower intelligence allocated more cognitive resources than children with higher intelligence. In addition, the results revealed a negative association between pupil dilation and a parent-report measure of sub-clinical symptoms of ASD, suggesting that children with fewer ASD-related symptoms allocated more cognitive resources than children who showed more sub-clinical symptoms of ASD. Both associations were independent of each other and could not be explained by variation in chronological age. These findings extend previous research demonstrating associations between basic aspects of visual processing and intelligence. In addition, these findings comport with recent theories of ASD that emphasize reduced sensitivity to the reward value of social situations. When confronted with social ambiguity, children with more ASD-related symptoms allocated fewer cognitive resources to resolving this ambiguity than children who showed fewer sub-clinical symptoms of ASD.

Keywords

Autism Spectrum Disorder; Pupil; Joint attention; Gaze following; Intelligence; Broad autism phenotype

1. Introduction

For several decades researchers have used the visual system as a window into the cognitive functioning of infants. Early studies conducted in the 1980s used habituation paradigms to

measure the rate of decay in looking time across repeated presentations of the same stimuli. Results showed that “short-looking infants” (i.e., infants with faster rates of decay) require shorter familiarization durations to demonstrate preference for a novel stimulus, and use qualitatively different scanning pattern than “long-looking infants.” That is, while the “short-looking infants” focused on global features first, “long-looking infants” began by focusing on the local features of the presented stimuli (Freeseaman, Colombo, & Coldren, 1993). Most importantly, individual differences in infant habituation patterns have been shown to predict intelligence scores up to 18 years later (Bornstein & Sigman, 1986; Colombo, 1995; Fagan & Singer, 1983; Kavšek, 2004; McCall & Carriger, 1993; Sigman, Cohen, & Beckwith, 1997). One possible interpretation of the observed continuity in children's mental development is that “short-looking infants” may use more efficient information processing strategies (e.g., scanning, encoding) than “long-looking infants.” More efficient information processing strategies may also be reflected in the intelligent behavior of older individuals.

Recent neuropsychological theories suggest that temporal processing measures (e.g., rate of decay, response time), while useful, may provide a rather indirect metric for evaluating the processing demands associated with a specific task (Just, Carpenter, & Miyake, 2003). That is, tasks that make little demand on an individual's cognitive resources per unit of time, may still take a long time to complete. Alternatively, measures of pupillary dilation have been proposed as one possible option for evaluating the intensity of an individual's thought processes more directly. Changes in pupil dilation have been shown to reflect task demand during a variety of cognitive and linguistic tasks (see Just et al., 2003 for a more complete review). For example, during language comprehension tasks, larger increases in pupil size have been shown when processing syntactically anomalous vs. well-formed sentences (Beatty, 1982; Schluroff, 1982), and sentences containing lexical or syntactic ambiguity vs. unambiguous sentences (Ben-Nun, 1986; Schluroff et al., 1986).

The research reviewed above suggests that pupillary responses are a sensitive index of task demand. However, few studies have investigated how individual differences in innate or learned abilities (e.g., expertise, intelligence) moderate this association between task demand and pupillary responses. In a seminal study, Ahern and Beatty (1979) evaluated task-evoked pupil dilations as participants solved mental multiplication problems of varying difficulty. Results showed that individuals with greater scholastic aptitude showed smaller task-evoked pupil dilations than individuals with lower scholastic aptitude. Interestingly, this negative association between individuals' scholastic aptitude and pupil dilations was evident across all levels of task difficulty. These findings suggest that changes in pupil size may best be interpreted as a measure of resource allocation, reflecting the relation (i.e., the gap) between the amount of cognitive resources available for information processing, and the amount of cognitive resources that is actually invested to complete a specified task. Since individuals with lower innate or learned abilities have fewer cognitive resources at their disposal, they may have to invest more cognitive energy (i.e., a larger portion of their cognitive resources) to complete a given task than individuals with greater abilities (efficiency hypothesis; see also Heitz, Schrock, Payne, & Engle, 2008).

It is possible that individuals with higher scholastic aptitude tend to recruit automatic processing strategies when completing basic multiplication problems, while individuals with lower scholastic aptitude depend more heavily on effortful processes. Support for this hypothesis comes from a recent fMRI study where participants were tasked to complete a series of digit-symbol substitution problems (Rypma et al., 2006). Results suggest that individuals with slower processing speeds require more prefrontal executive control for optimal performance, while individuals with faster processing speeds rely more heavily on automatic processing based in parietal regions of the ventral prefrontal cortex. Thus, one may predict a positive correlation between ability level and pupil dilation for tasks that require effortful (as compared to automatic) processing (effort hypothesis). Consistent with this prediction, van der Meer et al. (2010) found that individuals with higher intelligence showed greater task-evoked pupil dilations when completing complex geometrical mental rotation tasks than individuals with lower intelligence. Very likely, the positive association between ability level and pupil dilation is evident only up to a certain level of task difficulty. That is, tasks that overload an individual's available resources are likely followed by pupillary constriction (Granholm, Asarnow, Sarkin, & Dykes, 1996). The cognitive mechanisms that underlie this characteristic constriction of the pupil during resource overload are poorly understood but are likely reflected in an individual's disengagement from a task that is too difficult and/or lacks intrinsic reward value.

The current study evaluates task-evoked pupil dilations while children complete a free-viewing task designed to elicit basic social-cognitive processes (i.e., triadic gaze following). Several studies have reported successful gaze following in typically developing infants as young as 3 to 6 months of age (D'Entremont, 2000; D'Entremont, Hains, & Muir, 1997; Scaife & Bruner, 1975). However, it is not until 12–18 months that children start to follow others' gaze behind visual obstructions (Brooks & Meltzoff, 2002, 2005), providing more direct evidence for children's emerging perspective taking abilities (Jao, Robledo, & Deák, 2010). Recent prospective longitudinal studies of children with Autism Spectrum Disorder (ASD) demonstrate that deficits in gaze following can be reliably detected as early as 12 months (Nadig et al., 2007). These deficits are generally described as a core deficit of ASD (Sigman, Dijamco, Gratier, & Rozga, 2004), are commonly evaluated as part of state-of-the-art diagnostic assessments (Lord et al., 2012), and partial accomplishments in gaze following have been linked to subsequent gains in spoken communication (Sigman & Ruskin, 1999; Siller & Sigman, 2008). Finally, subtle differences in gaze following evaluated using eye tracking technology have been linked to features of the broad autism phenotype in samples of typically developing children (Swanson, Serlin, & Siller, 2013) as well as healthy college students (Swanson & Siller, 2013a).

The aim of this research is to evaluate the extent to which child characteristics (i.e., intelligence, sub-clinical symptoms of ASD) moderate the relation between task difficulty (i.e., congruent vs. incongruent gaze following condition) and pupil dilation (i.e., resource allocation). In the congruent condition, children viewed videos that display an adult model that is gazing at a series of targets that appear and disappear in the four corners of the screen. In the incongruent condition, children viewed similar videos where the model's gaze moved equally as often but was not directed at the appearing/disappearing targets. These stimuli have been effectively used in a series of eye tracking studies with healthy college students

(Swanson & Siller, 2013a), typically developing children (Swanson et al., 2013), and children with ASD (Swanson & Siller, 2013b). Across all studies, children's gaze allocation in the incongruent but not the congruent condition was related to features of ASD. Since the videos in the incongruent condition violate social expectations, we expect that these stimuli elicit more effortful (as compared to automatic) processing than the videos in the congruent condition. To ensure that the gaze following abilities are firmly consolidated in children's behavioral repertoire, we tested our hypotheses in a sample of children who ranged in age between three and nine years.

Given that in typically developing children, gaze following is a highly automatized neuropsychological process, we predict that children's pupil dilations in the incongruent (but not the congruent) condition are negatively related to children's intelligence. That is, we predict that children with lower intelligence allocate more cognitive resources in the incongruent condition than children with higher intelligence. In addition, we predict that children's pupil dilations in the incongruent (but not the congruent) condition are negatively related to sub-clinical symptoms of ASD (i.e., positively related to social abilities). Our previous research has shown that, when presented with the incongruent stimuli, children with more ASD-related symptoms allocated more gaze time to the target, and less gaze time to the model's face, when compared to children with fewer ASD-related symptoms. Thus, we predict that children with more sub-clinical symptoms of ASD invest fewer cognitive resources to following the model's gaze in the incongruent condition than children with fewer sub-clinical symptoms of ASD.

2. Methods

2.1. Participants

Fifty typically developing children (27 boys and 23 girls) between 3 and 9 years of age participated in a single laboratory assessment session lasting approximately 120 min. The research protocol was approved by the Hunter College Institutional Review Board. Parental informed consent and child verbal assent was obtained from all children before testing commenced. The sample was diverse with regard to ethnicity/race (33% Hispanic, Latino, or Spanish, 33% African American, 16% Asian, 12% European American, 6% mixed/other origin) and household income (25% of the sample reported annual household incomes below \$20,000, 50% reported annual household incomes below \$40,000, and 75% reported annual household incomes below \$70,000). During the assessment session, we administered the joint attention paradigm, a standardized test of nonverbal cognitive abilities, and a parent-report measure evaluating sub-clinical symptoms associated with ASD. In addition, parents completed questionnaires probing about children's medical history and family demographics. All children had normal, or corrected to normal vision and were free of genetic conditions (e.g., Fragile X Syndrome, Down Syndrome, Tuberous Sclerosis, Angelman Syndrome) and developmental disorders (e.g., ASD). However, one child had previously received a diagnosis of Attention Deficit Hyperactivity Disorder (ADHD). Eleven children were excluded due to missing joint attention ($n = 10$; see below for details) or cognitive data ($n = 1$). Descriptive information on the 39 participants with complete data is provided in Table 1.

2.2. Assessment of nonverbal cognitive abilities

Children's nonverbal cognitive abilities were evaluated using the Special Nonverbal Composite Score of the Differential Abilities Scales-II (DAS-II; Elliott, 2007). The DAS-II is a comprehensive, individually administered, clinical instrument for assessing the cognitive abilities that are important to learning. The test may be administered to children between 2½ and 18 years of age. The Special Nonverbal Composite (DAS-SNC) is a standard score ($M = 100$; $SD = 15$) derived from four subscales (i.e., picture similarities, matrices, pattern construction, and copying). As noted above, one child did not complete the DAS-II and was excluded from all further analyses.

2.3. Assessment of sub-clinical symptoms of with ASD

Children's sub-clinical symptoms of ASD were evaluated using the Social Responsiveness Scale (SRS; Constantino, 2002). This parent-report questionnaire includes 65-items, covering 5 behavioral domains (social awareness, social cognition, social communication, social motivation, autistic mannerisms). Example items include "Is aware of what others are thinking of feeling" (social awareness) and "Does not join group activities unless told to do so" (social motivation). Parents are asked to respond to each item on a 4-point rating scale, with responses ranging from 'not true', to 'almost always true'. The scale has demonstrated excellent internal consistency (Cronbach's α scores $> .90$). Moreover, in order to screen for ASD in the general population, raw score cut-off points have been established for males and females (70 and 65, respectively; sensitivity = .77, specificity = .75; Constantino, 2002). The SRS has successfully been used to measure sub-clinical symptoms in siblings of children with ASD (Constantino et al., 2006) as well as children in the general population (Constantino & Todd, 2003). Although none of our research participants had a clinical history of ASD, 5 children (12.8%, all male) scored above the recommended clinical cut-off on this measure ($M = 75.2$, $SD = 4.76$, range = 71–82). All subsequent analyses were based on SRS T-scores.

2.4. Joint attention stimuli and data acquisition

The joint attention stimuli included 8 short videos, presented on a 17" LCD display monitor. Prior to presenting the stimuli, children were instructed to "just watch" and reminded to keep their eyes on the screen throughout the entire task. Each of the eight videos included four trials (32 trials total). Each trial began with the head and face of a model appearing in the center of the screen, looking straight into the camera for 4000 ms (simulating the model making eye contact with the participant). Next, a target unique to each video (i.e., popular cartoon characters, ©2011 Nintendo/Pokémon) appeared in one of the four corners of the screen and 500 ms later the model shifted her gaze to a corner for an average of 3850 ms, either congruent or incongruent. In the congruent condition, the model's gaze was directed at the target. In the incongruent condition, the model switched her gaze to a corner other than that where the target appeared. In both conditions, the model's gaze returned to the center of the screen 500 ms after the target disappeared, after which the next trial was presented (see Fig. 1 for a detailed timeline). In total, each participant viewed four congruent and four incongruent videos (16 congruent and 16 incongruent trials total).

Children's gaze pattern and pupil size were recorded using Tobii T60 eye-tracking technology (TOBII Technology AB). This technology is completely non-invasive, allowing for free movement of the head and body. Analyses evaluating children's gaze pattern were reported elsewhere (Swanson et al., 2013). Pupil sizes, in millimeters, were collected from both eyes at a rate of 60 recordings per second (60 Hz), from an average distance of 60 cm. Individual measurements were accurate to better than 0.05 mm. Preliminary data processing was completed using MAT LAB Version 7.7 (MathWorks, Inc.). For each trial, data acquisition focused on 3000 ms (i.e., six consecutive 500 ms intervals) that started with the first frame when the target appeared on the screen (see Fig. 1). The average pupil size during each 500 ms interval was corrected for baseline variation by subtracting the average pupil size during the 250 ms preceding the target onset. Intervals with incomplete pupil data (<250 ms of valid pupil recordings) were excluded from all further analyses. Average baseline-corrected pupil sizes for each interval in the incongruent and congruent condition were computed by calculating the average baseline-corrected pupil size across all valid intervals.

For 10 of the 50 participants who were tested for this study (20%), more than half of the 500 ms intervals had to be excluded due to incomplete pupil data. As noted above, these ten participants were excluded from all further analyses. Preliminary analyses revealed that these 10 children were significantly younger than the children who provided more complete pupil data, $t(48) = -4.36, p < .0001$. This suggests that the demands of our experimental paradigm may have been too strenuous for some younger children. No significant group differences were found with regards to children's nonverbal cognitive abilities or sub-clinical symptoms of ASD, $p > .20$. For the remaining 39 children (one additional child was excluded due to missing DAS scores), a total of 769 (20.53%) invalid intervals were excluded from the congruent condition, and 859 (29.77%) invalid intervals were excluded from the incongruent condition. Preliminary analyses evaluating data loss among the 39 participants included in our final sample revealed no significant association between the percentage of valid intervals and children's chronological age, gender, SRS T -scores, or DAS standard scores, $p > .20$.

3. Results

3.1. Pupillary dilation, nonverbal intelligence, and sub-clinical symptoms of autism

Previous research suggests that pupil dilation typically peaks about 1200 ms after the onset of the cognitive demand (Gagl, Wawelka, & Hutzler, 2011; van der Meer et al., 2010). To test our key hypotheses we specified a mixed model for repeated measures that incorporated baseline-corrected pupil dilations for intervals 3, 4, 5, and 6 as outcome (the interval between 1000 ms and 3000 ms after the target appeared on the screen). The model was specified with a random intercept, which is equivalent to a repeated measure analysis of variance. Statistical analyses were completed using SAS Proc Mixed (SAS, Version 9.2 Copyright ©2002-2008 SAS Institute Inc., Cary, NC, USA). Fixed effect predictors included experimental condition (i.e., congruent vs. incongruent), chronological age, nonverbal cognitive abilities (DAS-SNC), the condition-by-DAS-SNC interaction term, sub-clinical symptoms of ASD (SRS T -scores), and the condition-by-SRS T -score interaction term. We did not include an independent variable to represent time; thus, fixed effects are

best interpreted as predictors of average baseline-corrected pupil dilations for the entire two-second interval. Further, preliminary analyses revealed that the interaction between condition and chronological age was non-significant, $p > .20$, and thus not included in our final mixed model. Consistent with our hypotheses, results revealed significant interaction effects for the condition-by-DAS-SNC interaction term, $F(1,270) = 5.75, p < .05$, as well as the condition-by-SRS T -score interaction term, $F(1,270) = 4.14, p < .05$. Exploratory analyses revealed no evidence suggesting a three-way interaction between condition, DAS-SNC scores, and SRS T -scores. Details on the parameter estimates and the standard errors of the fitted mixed model are presented in Table 2. Graphical representations of the significant interaction effects are presented in Fig. 2.

3.2. Evaluating the interaction between condition and nonverbal cognitive abilities

We used three different strategies to interpret the nature of the significant condition-by-DAS-SNC interaction effect. First, we considered children's nonverbal cognitive abilities as a continuous moderator, influencing the relation between experimental condition and baseline-corrected pupil dilations. Specifically, we used a Region of Significance approach (Preacher, Curran, & Bauer, 2006) to identify the upper and/or lower values of the moderator (i.e., DAS-SNC scores) at which the congruent and incongruent condition differed significantly on the dependent variable (i.e., baseline-corrected pupil dilations). Results showed that the baseline-corrected pupil dilations of children with DAS-SNC scores below 111.5 ($n = 26, 67\%$) were significantly larger in the incongruent than the congruent condition. In contrast, the pupil dilations of children scoring above this value ($n = 13, 33\%$) did not reliably differ between the congruent and incongruent condition. The finding that significant numbers of participants fell both below and above this empirically derived boundary supports our interpretation that children's nonverbal cognitive abilities moderate the relation between condition and children's pupil dilation in meaningful ways. Moreover, it is noteworthy that increased resource allocation was not limited to children whose nonverbal cognitive abilities were delayed. That is, all children who scored below 111.5 on the DAS-SNC allocated additional resources in the incongruent as compared to the congruent condition.

A second, complementary way of probing the significant condition-by-DAS-SNC interaction focused on simple effects, evaluating whether the association between nonverbal cognitive abilities and pupil dilations was evident for both experimental conditions. Thus we specified two mixed models predicting children's baseline-corrected pupil dilations, one for the congruent and one for the incongruent condition. Fixed effect predictors included chronological age, DAS-SNC scores, and SRS T -scores. Results revealed that children's nonverbal cognitive abilities reliably predicted children's pupillary responses in the incongruent, $F(1,35) = 4.13, p < .05$, but not in the congruent condition, $F(1,35) = .27, p = .60$.

Finally, we used a graphical approach to illustrate how children's baseline-corrected pupil dilations changed as a function of time, and how these trajectories differed based on the experimental condition (i.e., congruent vs. incongruent) and children's nonverbal cognitive abilities. To generate the necessary estimates, we specified six mixed models, one for each

of the six 500 ms time intervals. Fixed effect predictors included in the model were identical to the original model. Based on each model, we calculated estimates for the congruent/incongruent condition, representing the baseline-corrected pupil dilations for children who scored 1 standard deviation below/above the sample average on the DAS-SNC (to generate these estimates, children's age and SRS *T*-scores were set at the sample average). Results are plotted in Fig. 3a. During the first 1000 ms after the target appeared on the screen, children showed a rapid decrease in pupil diameter. This pupil constriction occurred independent of the experimental condition or children's nonverbal cognitive abilities, and is likely attributable to changes in luminance associated with the appearing target. In the congruent condition, this initial constriction was followed by a gradual increase in pupil diameter. Importantly, the rate of this increase was not related to children's nonverbal cognitive abilities. A similar rate of gradual increase was also observed in the incongruent condition, but only for children with relatively high nonverbal cognitive abilities. In contrast, children who scored one standard deviation below average on the DAS-SCN showed a considerably steeper increase in pupil diameter. This increased pupil dilation is likely attributable to the increased allocation of cognitive resources. Thus, findings from this research suggest that children with lower nonverbal cognitive abilities allocated more cognitive resources in the incongruent condition than children with higher nonverbal cognitive abilities.

3.3. Evaluating the interaction between condition and sub-clinical symptoms of autism

We used the same three strategies to interpret the nature of the significant condition-by-SRS *T*-score interaction effect. First, results from the Regions of Significance analysis revealed that the baseline-corrected pupil dilations of children with SRS *T*-scores below 57.4 ($n = 30$, 77%) were significantly larger in the incongruent than the congruent condition. In contrast, the pupil dilations of children scoring above this value ($n = 9$, 23%) did not reliably differ between the two experimental conditions. Second, our analysis of simple effects found a significant association between children's SRS *T*-scores and pupillary responses in the incongruent, $F(1,35) = 4.97$, $p < .05$, but not in the congruent condition, $F(1,35) = .73$, $p = .40$. Finally, results from the graphical analysis are plotted in Fig. 3b. Overall, the results from these analyses are strikingly similar to the results from our analyses probing the condition-by-DAS-SNC interaction effect. The level of similarity is notable, given that both interaction effects were based on a single mixed model and therefore statistically independent of each other. In fact, children's SRS *T*-scores and DAS-SNC scores showed no significant association, $r(39) = -.20$, $p > .20$. Despite these similarities, the direction of the observed effects was inverted. That is, we found that children with lower SRS *T*-scores (i.e., children who showed fewer ASD-related symptoms) allocated more cognitive resources in the incongruent condition than children with higher SRS *T*-scores. Thus, while children with lower (as compared to higher) cognitive abilities allocated more cognitive resources when processing our experimental stimuli, children with lower social abilities (i.e., higher ASD-related symptoms) allocated fewer cognitive resources than children with more advanced social abilities.

4. Discussion

Measures of pupillary dilation provide a temporally sensitive, quantitative indicator of cognitive resource allocation (Hess & Polt, 1964; Verney, Granholm, & Marshall 2004). In the current study, we used measures of pupillary dilation to evaluate the allocation of cognitive resources while free-viewing two kinds of videos designed to elicit gaze following. In the congruent condition, children viewed videos that display an adult model that is gazing at a series of targets that appear and disappear in the four corners of the screen. In the incongruent condition, children viewed similar videos where the model's gaze moved equally as often but was not directed at the appearing/disappearing targets. This research involved children between 3 and 9 years of age, a time in development when gaze following abilities have been well consolidated in the behavioral repertoire of typically developing children, and had two major findings. First, results revealed a significant condition-by-nonverbal intelligence interaction effect, suggesting that the association between children's nonverbal intelligence and pupil dilation differed significantly between the two experimental conditions. In the incongruent but not the congruent condition, children with lower nonverbal intelligence showed greater pupil dilation than children with higher intelligence. Second, results also revealed a significant interaction between condition and sub-clinical symptoms of ASD. That is, in the incongruent but not the congruent condition, children with fewer ASD-related symptoms showed greater pupil dilation than children with more ASD-related symptoms. Both interaction effects were independent of each other as well as variation in children's chronological age.

This research extends previous findings suggesting concurrent and predictive associations between basic aspects of visual processing and global measures of intelligence. That is, previous research has linked faster rates of infant habituation to subsequent outcomes in intelligence (Sigman et al., 1997). Similarly, the current study suggests a concurrent association between task-evoked pupil responses and measures of intelligence. As predicted, the direction of the association is negative, suggesting that individuals with lower intelligence tend to invest more cognitive resources to process the presented gaze stimuli than individuals with higher intelligence. Due to the cross-sectional nature of this research, we are not able to draw firm conclusions about the causal mechanisms that underlie these correlational findings. On the one hand, it is possible that pupillary reactions to our experimental task capture the efficiency with which children perform fundamental cognitive operations (Vernon, 1983). On the other hand, it is intriguing to speculate that individual differences in how children process social experiences may either facilitate or interfere with their cultural and intellectual development. The ability to coordinate interest in external events or objects with other people (i.e., joint attention) constitutes an important milestone in children's emerging understanding that other people attend to, and have intentions toward external objects or events (Tomasello, Carpenter, Call, Behne, & Moll, 2005). By recognizing others as intentional agents, children are able to participate in cultural learning and acquire a broad range of social, communicative, and cognitive abilities. Early joint attention abilities have been shown to aid early information processing (Striano, Chen, Cleveland, & Bradshaw, 2006) and predict subsequent gains in the understanding and use of linguistic symbols (Baldwin, 1993a, 1993b; Houston-Price, Plunkett, & Duffy, 2006), theory

of mind abilities (Charman et al., 2000; Nelson, Adamson, & Bakeman, 2008), and intelligence (Smith & Ulvund, 2003).

Independent of individual variation in intelligence, the current research also revealed a significant positive association between children's social abilities (as indexed by the absence of sub-clinical symptoms associated with ASD) and pupil dilation. That is, children with fewer sub-clinical symptoms of ASD exerted more cognitive resources in the incongruent condition than children with more ASD-related symptoms. To reiterate, in the domain of cognitive functioning, greater abilities were associated with the allocation of fewer cognitive resources. In contrast, in the domain of social functioning, greater abilities were associated with the allocation of more cognitive resources. In our previous eye-tracking research that used the same experimental stimuli, we found that, in the incongruent condition, children with higher social abilities spent more time looking at the face, and less time looking at the target, than children with lower social abilities (Swanson et al., 2013). The current findings suggest that children with lower social abilities also exert less mental effort in the incongruent condition than children with higher social abilities. One possible interpretation of this finding is that the videos in the incongruent condition overwhelm the cognitive resources of children with lower social abilities, which is reflected in their disengagement from the task. Alternatively, it has long been known that pupil dilations increase with the activation of the sympathetic nervous system, which regulates overall arousal levels (Lowenfeld, 1993). Thus, when confronted with an ambiguous social situation, children with more sub-clinical symptoms of ASD may either be less likely to take note of this social ambiguity, or be less inclined to resolve this ambiguity by allocating cognitive resources, than children with fewer subclinical symptoms of ASD. This interpretation is consistent with recent characterizations of ASD, which give primacy to a reduced sensitivity to the reward value of social situations (social motivation hypothesis; Dawson, Bernier, & Ring, 2012).

Typically, behavioral milestones associated with the development of gaze following are evaluated during the first three years of life. The current study suggests that meaningful individual differences in the cognitive processing of gaze following stimuli continue to be manifest well after gaze following is firmly established in children's behavioral repertoire. One distinct advantage of the current paradigm is its feasibility with participants of a wide age range (children to adults) and ability levels. This is particularly important, since recent genetic research demonstrated the heritability of a diminished social motivation trait in multiplex autism families (Sung et al., 2005). To further investigate whether the current experimental tasks capture fundamental cognitive operations, or more specific social-cognitive processes associated with joint attention, future research should include non-social comparison condition. Further, longitudinal research designs would be helpful to evaluate the causal mechanisms that underlie the identified correlations.

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Fig. 1.

Joint attention eye-tracking stimuli. At the center of the screen, each video displayed the head and face of a model, while targets appeared and disappeared in each of the four corners. In the congruent condition, the model's gaze shifts to the corner of the screen where the target has appeared, whereas in the incongruent condition the model's gaze was directed elsewhere.

Fig. 2.
 Graphs depicting the interactions between (a) experimental condition and the DAS II Special Nonverbal Composite (DAS-SNC) and (b) experimental condition and SRS *T*-score.

Fig. 3.

Graphs depicting changes in baseline-corrected pupil dilations as a function of time representing the interactions between (a) experimental condition and the DAS II Special Nonverbal Composite (DAS-SNC) and (b) experimental condition and SRS *T*-score.

Table 1Participant characteristics, $n = 39$.

Variable	Mean	Standard deviation	Range
Chronological age			
Years: months	6:9	1:7	3:10–9:3
Nonverbal cognitive abilities (DAS-SNC)			
Age equivalent, years: months	7:3	2:2	3:7–11:6
Standard score	106.99	13.65	82–138
Sub-clinical autism symptoms (SRS)			
Raw-score	36.56	19.95	6–82
T-Score	52.38	9.37	38–73

Abbreviations: DAS-SNC, Differential Abilities Scales II, Special Nonverbal Composite; SRS, Social Responsiveness Scale.

Table 2

Parameter estimates (SE) of fixed effects and variance components from a random intercept model testing our key hypotheses.

	Parameter estimate (SE)
<i>Fixed effects</i>	
Intercept	-.0954 *** (.0132)
Chronological age	.0012 (.0006)
Condition	-.0309 ** (.0103)
Nonverbal cognitive abilities (DAS-SNC)	-.0028 (.0014)
Sub-clinical autism symptoms (SRS <i>T</i> -scores)	-.0032 * (.0014)
Condition × DAS-SNC interaction	.0019 * (.0008)
Condition × SRS <i>T</i> -score interaction	.0018 * (.0009)
<i>Variance components</i>	
Level-1, residual, σ_e^2	.0034 *** (.0003)
Level-2, intercept, σ_0^2	.0074 ** (.0018)

Note. The model was specified with a random intercept (RI). DAS-SNC, Differential Abilities Scales II, Special Nonverbal Composite; SRS, Social Responsiveness Scale.

*
 $p < .05$.

**
 $p < .01$.

 $p < .001$.