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

Valentyna Erstenyuk [a], Meghan R. Swanson [a,b,1], Michael Siller [a,b,*]

[a] Hunter College, City University of New York, 695 Park Avenue, New York, NY 10065, USA
[b] The Graduate Center of City University of New York, 365 Fifth Avenue, New York, NY 10016-4309, USA

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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.

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 (Freeseman, Colombo, & Coldren, 1993). Most

* Corresponding author at: Hunter College, 695 Park Avenue, Psychology Department, Hunter North 611, New York, NY 10065, USA. Tel.: +1 212 772 4477; fax: +1 212 772 5620.
E-mail address: msiller@hunter.cuny.edu (M. Siller).
[1] Present address: Carolina Institute for Developmental Disabilities, University of North Carolina at Chapel Hill, USA.

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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