Pupillometry correlates of visual priming, and their dependency on autistic traits

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In paradigms of visual search where the search feature (say color) can change from trial to trials, responses are faster for trials where the search color is repeated than when it changes. This is a clear example of "priming" of attention. Here we test whether the priming effects can be revealed by pupillometry, and also whether they are related to autistic-like personality traits, as measured by the Autism-Spectrum Quotient (AQ). We repeated Maljkovic and Nakayama's (1994) classic priming experiment, asking subjects to identify rapidly the shape of a singleton target defined by color. As expected, reaction times were faster when target color repeated, and the effect accumulated over several trials; but the magnitude of the effect did not correlate with AQ. Reaction times were also faster when target position was repeated, again independent of AQ. Presentation of stimuli caused the pupil to dilate, and the magnitude of dilation was greater for switched than repeated trials. This effect did not accumulate over trials, and did not correlate with the reaction times difference, suggesting that the two indexes measure independent aspects of the priming phenomenon. Importantly, the amplitude of pupil modulation correlated negatively with AQ, and was significant only for those participants with low AQ. The results confirm that pupillometry can track perceptual and attentional processes, and furnish useful information unobtainable from standard psychophysics, including interesting dependencies on personality traits.

Introduction

Priming is a well-known phenomenon in language and perception, where repeated presentation of a stimulus speeds subsequent responses to that stimulus. Priming also affects attention and visual search. Perhaps the clearest demonstrations are the now classic studies of Maljkovic and Nakayama (1994); Maljkovic and Nakayama (1996): when asked to identify the shape of a singleton target defined by color as the odd-one-out (see Figure 1A), participants responded more quickly when the target color was repeated over trials than when it changed, with the priming effects accumulating over many trials. Similar results have been observed for a number of different visual features, including color, orientation, shape, motion and size (Becker, 2008; Campana, Pavan, & Casco, 2008; Fecteau, 2007; Goolsby & Suzuki, 2001; Kristjánsson, 2006, 2009; Lamy, Carmel, Egeth, & Leber, 2006; Magnussen & Greenlee, 1999; Maljkovic & Nakayama, 1994; McBride, Leonards, & Gilchrist, 2009; Wolfe, Butcher, Lee, & Hyle, 2003).

This line of research has shown that attention and perception can be strongly influenced by past perceptual history. Neurotypical adults track the statistics of the environment and combine past information with

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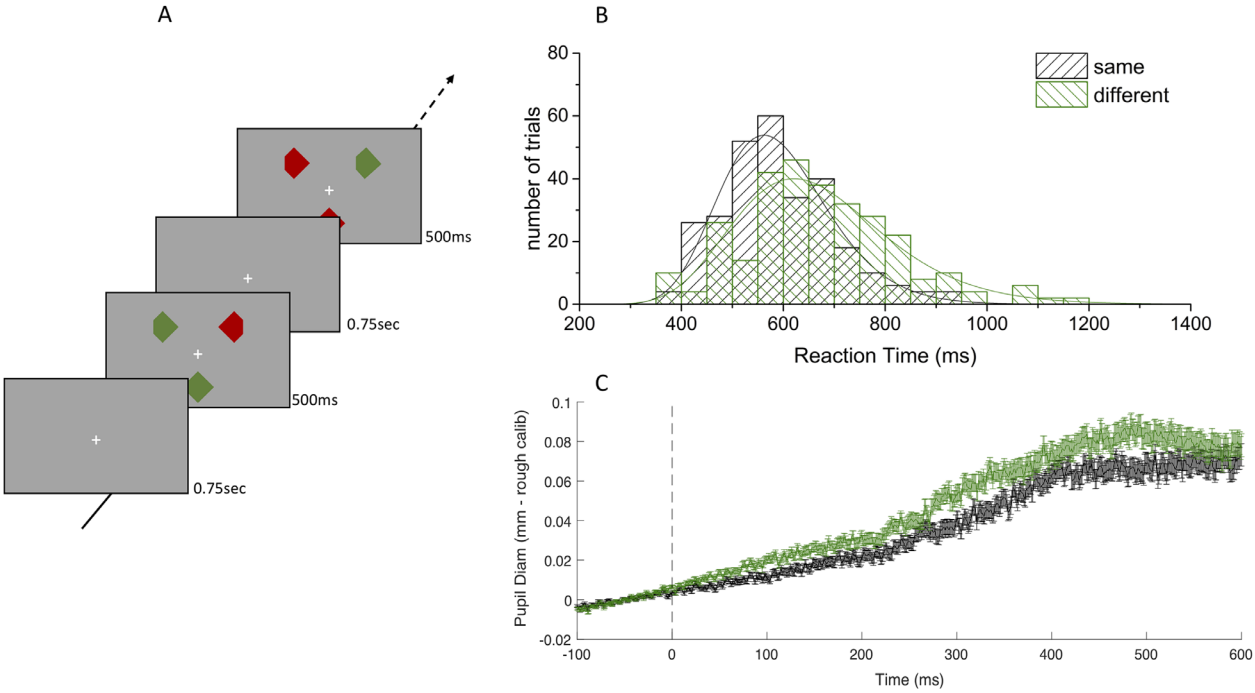

Figure 1. Schematic representation of the stimuli together with an example of subject reaction time distributions and pupil modulations. (A) The task was to identify the side cut off the odd-colored diamond. The target was positioned randomly left or right, always above of fixation. The participant's task was to report which side of the odd-colored diamond was missing; after the response a blank display with fixation cross remained for 750 ms. (B) Distributions of reaction times for one example subject for both repeated trials (black) and switched trials (green), with best-fit Gaussian functions. (C) Pupil size recordings plotted as a function on time from 100 ms before the trial onset (considered as baseline and subtracted from each trace and then averaged across subject) to the stimulus offset. Vertical dashed line marks the onset of the stimulus. Error bars show SEM.

current sensory data to improve efficiency in processing of incoming stimuli (Cicchini, Anobile, & Burr, 2014; Cicchini, Mikellidou, & Burr, 2017; Fischer & Whitney, 2014). Imperfect predictions are thought to elicit a prediction error (Friston, 2005), which promotes learning through updating of an internal model (Nassar, Wilson, Heasly, & Gold, 2010; Burr & Cicchini, 2014). On this view, perceptual decisions are made by comparing the probability of the sensory evidence with prior experience. The Bayesian class of theories—including predictive coding and other generative models (Kersten, Mamassian, & Yuille, 2004; Knill & Pouget, 2004)—assumes that perception is an optimized combination of the *likelihood* (sensory data) and the *prior* (influences based on previous perceptual history). Importantly, the expectations are perceptual in nature, and seem to be obligatory, not under cognitive control. In a crucial experiment, Maljkovic and Nakayama (1994) alternated the target color between trials, so color was perfectly predictable but always changed: average reaction times under this condition were slower than totally unpredictable random alternation, showing that a cognitive knowledge of target color could not by itself prime the next trial to speed up responses. However, although cognitive knowledge does not seem to interfere with priming, other studies have shown that expectancy can affect it (Müller, Reimann, & Krummenacher, 2003; Wolfe, 1994; Wolfe et al., 2003).

Individuals vary considerably in perceptual style, especially in the extent that they use perceptual priors predictively. In particular, it has been suggested that autism spectrum disorders are associated with weak or less adaptable priors (Pellicano & Burr, 2012), so their perception is dominated more by sensory information than past experience. This concept has been reinforced by several other proposals along similar lines (Friston, Lawson, & Frith, 2013; Lawson, Rees, & Friston, 2014; Rosenberg, Patterson, & Angelaki, 2015; Sinha et al., 2014), and has received empirical support from studies showing diminished adaptation in autistic individuals in the processing of faces (Pellicano, Jeffery, Burr, & Rhodes, 2007; Pellicano, Rhodes, & Calder, 2013) and non-face stimuli (Turi et al., 2015; Turi, Karaminis, Pellicano, & Burr, 2016). This is in line with recent studies on how people on the autism spectrum use sensory statistics to update their internal model (for a review see Robertson & Baron-Cohen, 2017). Some evidence suggests that autistics are slower to update prediction, so it is more dominated by earlier past

(Lieder et al., 2019), and that autistic adults tend to rely less on learned priors when asked to discriminate sensory representation in a volatile environment, showing less response to surprising events (Lawson, Mathys, & Rees, 2017). On the other hand orientation of attention in visual search was found to be intact in ASD (e.g., Grubb et al., 2013).

Pupillometry is proving to be a powerful tool for this line of research. The pupil responds primarily to changes in light, but in recent times has also been used as a marker of cognitive and emotional load, and reaction to the unexpected (Binda, Pereverzeva, & Murray, 2014; Bradley, Miccoli, Escrig, & Lang, 2008; Chiew & Braver, 2014; Lavín, San Martín, & Rosales Jubal, 2014; Preuschoff, 't Hart, & Einhäuser, 2011; Renninger, Carney, Privitera, Klein, & Aguilar, 2010). Experiences associated with surprise (i.e. changing sensory evidence) tend to induce pupil dilation via the rapid release of norepinephrine (Preuschoff et al., 2011). Therefore measuring pupil diameter may provide an objective index of the strength of prior expectations in individual observers. Pupil-size can also predict top-down perceptual effects. For example, images of the sun cause more pupillary constriction than do luminance-matched scrambled images, or images of the moon (Binda, Pereverzeva, & Murray, 2013a)—even when rendered as cartoons (Naber & Nakayama, 2013). And simply attending to a bright or dark surface can change pupil-size (Binda, Pereverzeva, & Murray, 2013b). The method is noninvasive and lends itself well as an objective monitor of perceptual processes.

Using pupillometry, Turi et al. (2018) showed that pupil diameter oscillated in phase with the ambiguous perception of a bistable rotating cylinder, more dilated when the black surface was in front. Importantly, the magnitude of oscillation varied between participants and was strongly correlated with autistic traits, defined by the Autism-Spectrum Quotient AQ (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001). The effect was far stronger in participants with high AQ, consistent with high AQ (and autistic) individuals having a local, detail-oriented perceptual style. These and other results (e.g., Tortelli, Turi, Burr, & Binda, 2018) show that pupillometry can be more sensitive than standard behavioral measures (including RTs) in revealing subtle interindividual differences in the deployment of attention and perception.

In the current study, we investigated whether pupillometry can reveal the effects of perceptual priming, and whether the pupillometry and reaction-time effects covary with personality traits. We tested 27 randomly selected neurotypical adults with variable degrees of AQ-defined autistic traits. We hypothesized that change of the target color should cause a measurable increase in pupil size compared with repetition of target color, reflecting a "surprise" reaction to the violation of perceptual expectancy. We further speculated that there could be a reduced pupillary response to violation of perceptual expectancy in the group with high autistic traits, reflecting their lesser dependency on prior information.

Materials and methods

Participants

Twenty-seven participants (22 female, age [mean ± SD]: 24.4 ± 2.45) with corrected-to-normal vision took part in the experiment. All participants reported no diagnosed neurological condition. This sample size was deemed to be appropriate to obtain a moderate effect size with $\alpha = 0.05$ and power of 0.8. Experimental procedures were approved by the regional ethics committee (*Comitato Etico Pediatrico Regionale—Azienda Ospedaliero-Universitaria Meyer*—Florence) and are in line with the declaration of Helsinki; participants gave their written informed consent.

AQ score

All participants completed the self-administered Autistic Quotient questionnaire, in the validated Italian version (Ruta, Mazzone, Mazzone, Wheelwright, & Baron-Cohen, 2012; Ruzich et al., 2015). This contains 50 items, grouped in five subscales: Attention Switching, Attention to Detail, Imagination, Communication and Social Skills. For each question, participants read a statement and selected the degree to which the statement best described them: "strongly agree," "slightly agree," "slightly disagree," and "strongly disagree" (in Italian). The standard scoring described in the original paper was used: 1 when the participant's response was characteristic of ASD (slightly or strongly), 0 otherwise. Total scores ranged between 0 and 50, with higher scores indicating higher degrees of autistic traits. All except one participant (with AQ 37) scored below 32, the threshold above which a clinical assessment is recommended (Baron-Cohen et al., 2001). The median of the scores was 15, with lower and upper quartiles of 12.2 and 21.2. Scores were normally distributed, as measured by the Jarque-Bera goodness-of-fit test of composite normality (JB = 4.12, $p = 0.13$).

Stimuli and procedure

All trials started with a white fixation cross at screen center on a dark background following a search display containing three diamond shapes, 0.84° × 0.84°, with 0.15° cut off either the left or right side (see Figure 1A).

Observers searched for the odd-colored diamond (either a red target among two green distractors or vice versa) and reported its shape (cutoff on left or right side) by rapidly pressing the appropriate button on the keyboard. As in the study of Maljkovic & Nakayama (1996) the target stimulus was always above the fixation cross, either left or right. The duration of the target was 500 ms, with an intertrial pause of 750 ms, following the participants' responses. The target color either switched or repeated on each trial with equal probability. After a 10-trial training session, participants performed four 80-trial sessions. While performing the behavioral task, pupil size of participants was recorded (see *Apparatus*). To prevent luminance driving pupil size, the background, the red and green diamonds all were equiluminant at 14.8 cd/m^2.

Apparatus

Participants were seated in front of the computer monitor in a dark room with chin resting on a chin-rest at a distance of 57 cm. Stimuli were generated with the PsychoPhysics Toolbox routines (Brainard, 1997) for MATLAB (r2016b, The MathWorks) and presented on a 39 cm monitor (120 Hz, 800 × 600 pixels; Barco Calibrator). Eye position and pupil diameter were monitored at 1000 Hz with an infrared camera mounted below the screen (Eyelink1000 Plus, SR Research). Pupil diameter measures were transformed from pixels to millimeters after calibrating the tracker with an artificial 4-mm pupil, positioned at the location of participant's left eye.

Time points with unrealistic pupil size (less than 2 mm) were considered to be signal losses and were removed from the analysis. The first trial of each session was also excluded because there was no possibility of priming. To measure the pupillary response evoked by the stimuli, individual data were baseline-corrected by subtracting the average diameter within the 100-ms window preceding the stimulus presentation. The time course of the pupillary response was determined by averaging baseline-corrected data in 150-ms bins. We restricted our analysis of pupil size to a specific time window from 100 to 600 ms (just after the stimulus disappearance, and before the button-press dominated the pupillary response). We verified that shifting this window or shrinking it by 100 ms did not change the pattern of results. Only data from correct trials were analyzed.

Standard *t*-tests and correlation analyses were complemented with Bayes Factors estimation. The JZS Bayes Factor (Rouder, Speckman, Sun, Morey, & Iverson, 2009) quantifies the evidence for or against the null hypothesis as the ratio of the likelihoods for the experimental and the null hypothesis. It can be expressed as the logarithm of the ratio (Jeffreys, 1961; Kass & Raftery, 1995), where negative numbers indicate that the null hypothesis is likely to be true, positive that it is false. By convention, absolute log Bayes factors greater than 0.5 are considered substantial evidence for or against, and absolute log-factors greater than 1 strong evidence.

To estimate the effect of internal reliability on correlations, we also calculated the "disattenuated correlation" index, which takes into to account internal reliability by normalizing the geometric mean of estimates of the internal reliability of each measure. We assessed internal reliability with either Cronbach's alpha, for AQ, and with split-half reliability adjusted with the Spearman-Brown proficiency formula (Spearman, 1904; Spearman, 1910), for pupil-change and reaction-times data.

Results

Priming revealed pupil changes

We measured reaction times (RTs) for identifying the shape of the odd-colored diamond, while monitoring pupil size. Figure 1 shows for one example subject reaction time distributions and pupil modulations for both repeated (black) and switched (red) trials. Responses for repeated trials were faster than to switched trials, in this case by nearly 100 ms (mean ± SEM: repeated 591.9 ms ± 6.5; switched 672.1 ms ± 8.9). Figure 1C illustrates the average time course of the pupillary response for the same example participant. There is a clear tendency for switch trials to elicit larger pupil dilation, averaged over the range of 100 to 600 ms (mean ± SEM: repeated 0.0390 mm ± 0.0035; switched 0.0503 mm ± 0.0037).

Figure 2 shows data for all 27 participants. As we were interested in the effect of autistic personality traits on the results, we divided participants into low AQ (blue) and high AQ (red), based on a median split of their AQ scores (above or below 15). Figure 2A plots individual reaction times to repeated trials against those to switched trials. The data of all except one participant fell below the equality line, showing that RTs were faster for the repeated condition, consistent with a priming effect for reaction times. The blue and red data points are intermixed, with no difference in the performance of participants with low and high AQ scores. This is clear from the average results, plotted as stars in Figure 2A, and also the average data points in Figure 2C (left). A mixed model two-way analysis of variance (ANOVA) shows a significant main effect of the within-subject factor "priming" (repeated vs. switch trials, $F_{(25,1)} = 51.73$, $p < 0.001$), but no effect of the between-subject factor AQ (low or high, $F_{(25,1)} = 1.37$, $p = 0.25$), and no interaction between factors ($F_{(25,1)} = 0.082$, $p = 0.77$).

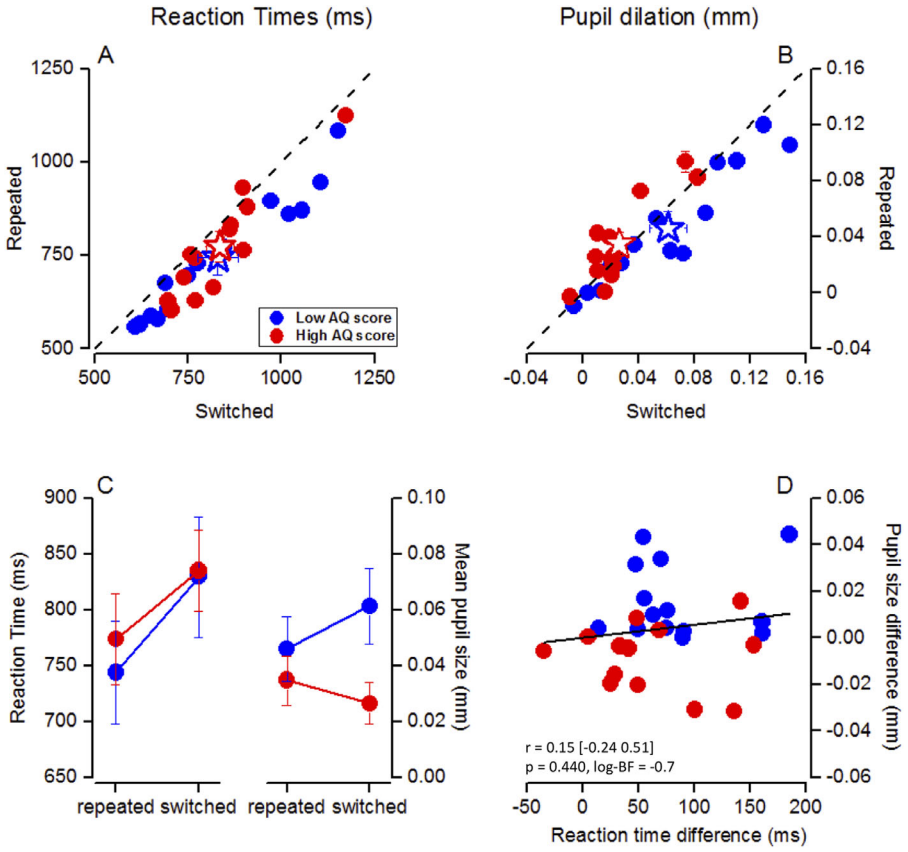

Figure 2. The effect of switching target color on reaction times and pupil-size changes. (A) Reaction times for repeated trials plotted against switched trials for the 27 participants. Blue refers to participants with low AQ, red to high AQ. Empty stars show the color-coded means for the subsample of participants. (B) Changes in pupil size for repeated trials plotted against switched trials for the same participants (color conventions as in A). (C) Mean reaction times (left panel) and pupil size (right panel) for the two subsamples of participants for both repeated and switched trials. (D) Correlation between the pupil dilation difference (measured as the difference between pupil size during switched and repeated trials) and reaction time difference (measured as the difference between reaction times during switched and repeated trials). Text inset reports Pearson's Rho value and associated p-value and Bayes Factor. Thick black line shows the linear fit through the data.

Figure 2B plots pupil change for repeated against switched trials. Here, low and high AQ participants form distinct clusters, with low AQ points tending to fall below the equality line. Again this is best seen in the plot of average results, shown by the stars of Figure 2B and the right half of Figure 2C. There is stronger pupillary dilation in the switched-color trials, but only for the group of low AQ. This is confirmed by the two-way ANOVA, which reveals a significant interaction between the within-subject factor "priming" and the between-subject factor AQ ($F_{(25,1)} = 16.16$, $p < 0.001$), but no effect of the between-subject factor AQ ($F_{(25,1)=}2.57$; $p = 0.12$) and no main effect of the within-subject factor "priming" ($F_{(25,1)}= 1.42$, $p = 0.24$).

These analyses suggest that both RTs and pupil dilation are related to priming effects, but in qualitatively different ways. To bring this out more clearly, Figure 2D plots the effect of priming on pupil dilation (the difference between the average change in pupil size for the switched and the repeated targets) as a function of the priming effect on reaction times (the difference of RT during switched trials and repeated trials). There is substantive evidence that the two measures do not correlate with each other (r = 0.15 [−0.24 0.50], $p = 0.440$, logBF = −0.7), suggesting that these two indexes—pupillary and behavioral—capture different aspects of the priming phenomenon. To check that this lack of correlation did not result solely from poor internal reliability of our measures, we also calculated the "disattenuated correlation," which takes into to account internal reliability, by normalizing the geometric mean of Cronbach's alpha of each measure. The internal reliability (calculated by split-half reliability adjusted with Spearman-Brown proficiency formula) was 0.71 (logBF = 2.86) for RTs and 0.35 (logBF = −0.14) for pupil size. Although these are not particularly high (especially pupil-size), normalizing

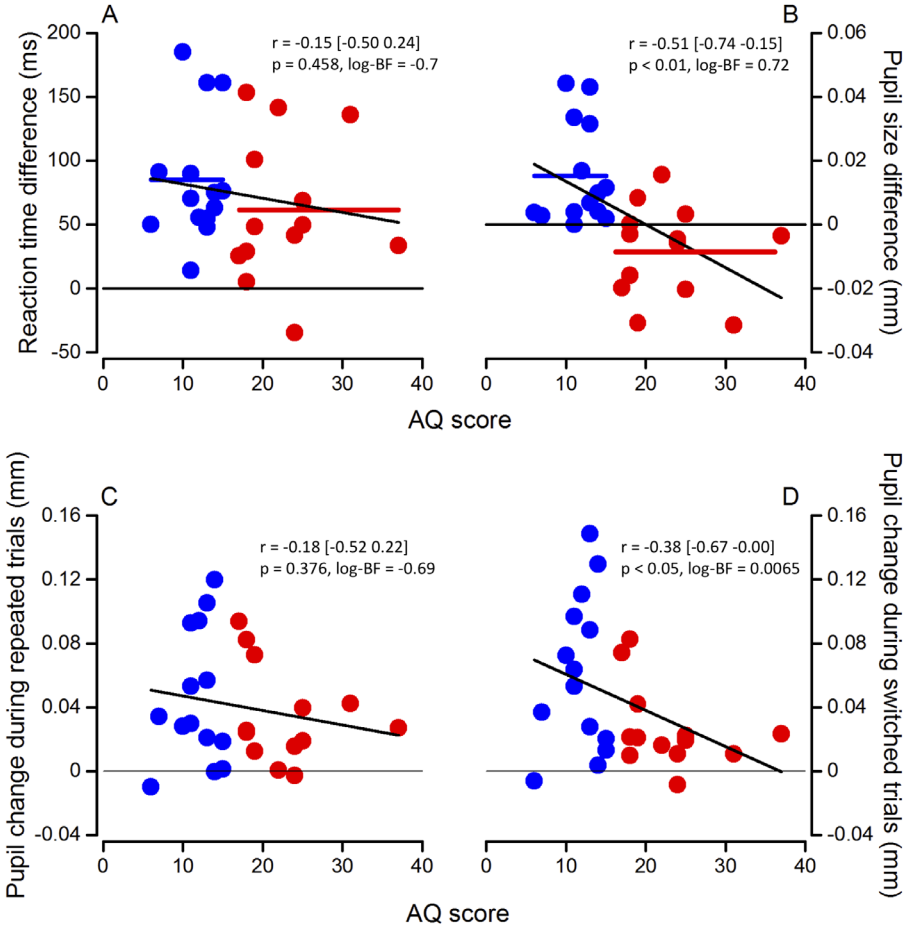

Figure 3. Correlations between Autistic Quotient and reaction times and pupil-dilation. (A) Reaction time difference and pupil size difference (B) plotted against AQ scores for all participants (low AQ in blue and high AQ in red). (C) Pupil changes during repeated trials and switched trials (D) plotted against AQ scores. Thick color-coded horizontal lines represent the means of the two groups. Text insets report Pearson's Rho values and associated *p*-values and Bayes Factors. Thick black lines show the linear fit through the data.

by these leads to a disattenuated correlation of 0.30, LogBF = −0.33. The Bayes factor is not substantial, but there is no evidence for a significant correlation between the two measures.

Relationship with AQ

We then examined in more detail the relationship between AQ and priming effects on RTs and pupil dilation. Figure 3A plots the effect of priming on reaction times against AQ scores, showing substantive evidence of there being no correlation (r = −0.15 [−0.50 0.24] $p = 0.458$, logBF = −0.7). The disattenuated correlation was 0.22, logBF = −0.56. On the other hand, Figure 3B shows that the priming effect on pupil dilation is substantially correlated with AQ scores (r = −0.51 [−0.74 −0.15] $p < 0.01$, logBF = 0.72; disattenuated correlation > 1), reinforcing the results from the median split. We further explored the correlation separately for pupil changes during repeated (Figure 3C) and swapped trials (Figure 3D). While changes on repeated trials did not correlate with AQ scores (r = −0.18 [−0.52 0.22], $p = 0.376$, logBF = −0.7), those during switched trials do show a negative correlation (r = −0.38 [−0.67 −0.00], $p < 0.05$, logBF = 0.0065). The disattenuated correlations were r = −0.23 (logBF = −0.52) and r = −0.48 (logBF = 0.59) for repeated and switched trials. This is consistent with Figure 2C, showing a greater difference between the high and low AQ groups for switched than for repeated trials.

Accumulation of effects

To better understand the build-up of priming and pupillary effects, we analyzed the data further, looking at the effect of past history, up to 5 trials back, restricting the analysis to the low AQ group (which had significant pupil-size effects). Figure 4A shows that the

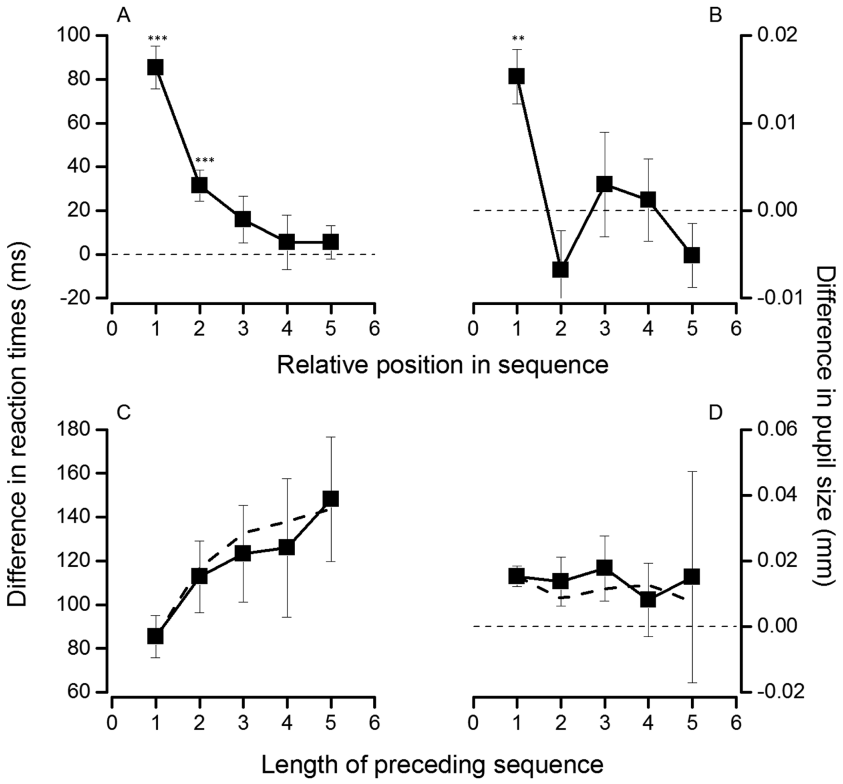

Figure 4. Serial dependence of repeating target color for both reaction times and pupil size. (A) Reaction time differences in ms and (B) pupil size differences in mm (switched trials – repeated trials), as a function of the relative serial position of the repeated color in the trial sequence. (C) Reaction time differences in ms (D) and pupil size differences in mm as a function of the length of the same-color sequence. Dashed lines are the integrals of data in panels A-B, respectively. Significance values refer to one sample T-test (**$p < 0.01$, ***$p < 0.001$).

RT advantage caused by the presentation in a previous trial of the same target color is strongest when the prime immediately preceded the current stimulus ($t_{(13)} = 6.45$, $p < 0.001$, logBF = 3.04), then decreases as a function of distance in the sequence. The difference remains significant for 2 trials back ($t_{(13)} = 4.54$, $p < 0.001$, logBF = 1.81), then fails to reach statistical significance (all other $p > 0.1$, logBF < 0.15). Figure 4C plots the priming effect for sequences of the same-color, as a function of the length of the preceding sequence of the same color. The priming effect is clearly cumulative, following closely the prediction obtained by integrating the individual effects of Figure 4A (shown by the dashed line). The linear regression of this function has a slope of 15.95 ms (±2.46) statistically different from zero (t=6.48, $p = 0.007$, logBF = 0.27).

Figure 4B shows that, unlike RTs, the effects on pupil-size do not last more than the immediate change. While the effects 1-back are significant ($t_{(13)} = 3.60$, $p < 0.01$, logBF = 1.16), none of the other comparisons for trials further back in the sequence reach significance (all $p > 0.1$, logBF = −0.5). Similarly, there was no accumulation of the effect for long repetitions (Figure 4D): the effects for all run-lengths of repeated sequences were statistically indistinguishable ($F_{(52,4)} = 0.069$; $p = 0.991$) and the slope of this function was −0.001 mm (± 0.001), not statistically different from 0 ($t = -1$, $p > 0.3$, logBF = −0.13).

Position priming and dependency on response

In their original studies, Maljkovic and Nakayama (1996) showed that there was a reaction-time advantage not only when the target color was repeated, but also a smaller advantage when the position of the target was repeated. Figure 5A shows that our RT results also show positional priming. However, in our experiment, the positional priming seems to be confined to trials that did not switch color. Reaction times were about 46 ms faster when the target was presented to the same position for conditions when the target color did not change, but very similar when the target color did change (with a difference of about 10 ms). Three-way ANOVA revealed a significant within-group main effect of position ($F_{(25,1)} = 10.24$, $p = 0.004$), as well as a significant interaction with color ($F_{(25,1)} = 5.93$, $p = 0.02$). However, there was

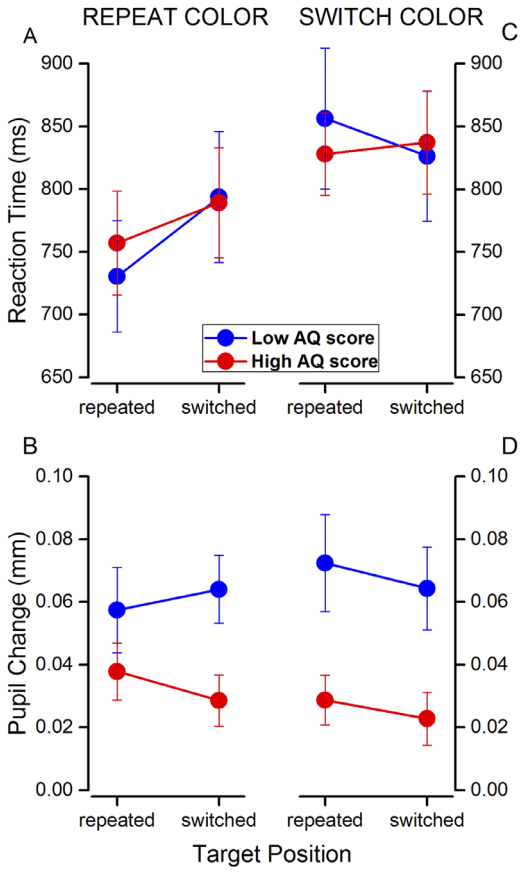

Figure 5. Priming of position for reaction time and pupil size. Mean reaction time (A) and mean pupil size (B) for repeated color trials as a function of the position of the target in the sequence. Mean reaction time (C) and mean pupil size (D) for switched color trials as a function of the position of the target in the sequence. Different colors represent different Autistic Traits (low AQ score in blue; high AQ score in red).

no interaction with AQ ($F_{(25,1)}$=3.55, $p = 0.07$), nor was there a significant correlation between AQ and the reaction-time advantage for position (r= −0.08, p= 0.05, logBF = 0.006–not shown).

Figures 5B&D show the dependence of pupil diameter on repetition of position. A three-way ANOVA shows no main effect of AQ ($F_{(25,1)} = 3.02$, $p = 0.09$). Nor was there a main effect of target position ($F_{(25,1)} = 0.67$, $p = 0.41$), or an interaction between AQ and position ($F_{(25,1)} = 0.001$, $p = 0.97$).

As some recent evidence (Yashar & Lamy, 2011) suggests that repetitions of motor responses interacts with the repetitions of the target defining features, we performed a two-way repeated measures ANOVA, with between subject factor AQ, for both reaction times and pupil size separately. We found no interaction between repeating the target feature and repeating the motor response, neither for RTs ($F_{(25,1)} = 0.345$; $p = 0.56$) nor pupil size ($F_{(25,1)} = 0.287$; $p = 0.6$). Nor did we find any main effects of motor response ($F_{(25,1)} = 3.94$; $p = 0.06$ for RT; $F_{(25,1)} = 0.05$; $p = 0.8$ for pupil size), nor an interaction between the two measures and AQ (RTs: $F_{(25,1)} = 0.44$; $p = 0.5$; Pupil size: $F_{(25,1)} = 0.62$; $p = 0.4$). We also analyzed the effect of long runs of motor repetitions on both Rts and pupil size, as studies (Lamy, Bar-Anan, & Egeth, 2008) have reported stronger effects after consecutive repetition. We found that motor repetition facilitation of reaction times became apparent only after four response repetitions ($F_{(78,3)} = 4.26$; $p = 0.008$). However, even for 4 repetitions, there was no effect on pupil size ($F_{(78,3)}$=1.052; $p = 0.37$).

Potential artifacts

Because a major conclusion of this article is that the greater pupillary response to switched than to repeated trials depended on AQ, it is important to exclude the possibility that the pupillary dependency on AQ did not result from a generalized AQ-dependent difference in pupil responsivity. This is not implausible, because it has been reported that pupil metrics such as baseline pupil size and stimulus-evoked changes are abnormal among autistic individuals (Anderson, Colombo, & Unruh, 2013; Martineau et al., 2011). However, we believe this is unlikely in this study. Firstly, AQ correlated only with responses to switched trials, not to repeated trials, as would be expected if there were a generalized change in responsivity. We also ran 2 further analyses, correlating both baseline pupil size (averaged over the 100 ms preceding the response) and the late pupillary response (averaged over the time window 1000–1500 ms after stimulus presentation), mainly generated by button-press. Neither correlation approached significance: baseline r = 0.23; $p = 0.25$; logBF = −0.5 (disattenuated r = 0.28; logBF = −0.37); response to button-press r = 0.08; $p = 0.69$; logBF = −0.8 (disattenuated r = 0.10; logBF = −0.77). These non-correlations preclude the possibility that the results are driven by a generalized dependency of either baseline or stimulus-evoked pupil response on AQ.

Subjects were asked to fixate throughout the trials, and eye-movements were monitored. The average root-mean squared deviation from fixation was 0.77°. As eye-movements can change the estimate of pupil size (Hayes & Petrov, 2016), which could in turn artificially drive our results, we checked whether eye-movement amplitude correlated with any relevant variables. It did not. The correlation with AQ was r = −0.05; $p = 0.80$; logBF = −0.8; disattenuated r= 0.06; logBF= −0.80), and the correlation with average pupil-size was (r = −0.25, $p = 0.20$, logBF = −0.5; disattenuated r= −0.26; logBF = −0.44). Nor was there a correlation with difference in pupil-size (r = −0.30, $p = 0.12$, logBF = −0.3; disattenuated r = 0.60; logBF = 1.56).

We can therefore safely rule out the possibility that eye-movement related artifacts in pupil-size influenced our results.

Discussion

This study used pupillometry to investigate perceptual priming of pop-out. Our results show that priming does affect pupillometry indices, but these effects are different from those on reaction times. We replicated Maljkovic and Nakayama's (1994) results of robust speeding of reaction times on repetition of the priming color, and showed that this priming effect does not depend on autistic-like personality traits, as measured by AQ scores. We also confirmed Maljkovic and Nakayama's (1996) observation that reaction-times were also facilitated (to a lesser extent) by repeated position of the target, and the effect also did not depend on AQ.

The main new result of this study was that the pupillary dilation on stimulus presentation was greater for trials when the target color switched than when it remained the same as the previous trial. Importantly, this effect depended strongly on the AQ of participants, to the extent that it was observed only in participants with lower than median AQ. The dependence on AQ was strongest for the switched trials, suggesting that it was the switch that drove the effect, consistent with a response to violation of perceptual expectancy. There was no measurable effect of position priming on change in pupil-size.

The two reported effects of priming—reaction times and pupil dilation—seem to be independent of each other. The two measures did not correlate with each other across participants (even after dissattenuation for internal reliability), as would be expected if they shared common mechanisms. Furthermore, whereas pupil response depended on AQ, reaction times did not. And whereas the effect on reaction times occurred for stimuli two or three trials back in the sequence, and accumulated over trials (agreeing with Maljkovic and Nakayama (1994)), the effect on pupil dilation depended only on the previous trial being different, with no accumulation over trials.

Priming of pop-out is a specific example of the effect of history on performance. Unlike other examples where history affects perception directly such as serial dependence (Cicchini et al., 2014; Fischer & Whitney, 2014), priming of pop-out is considered to result from the effect of history on attention, which in turn affects reaction times. That the magnitude of the attention-priming did not depend on AQ is interesting, especially in the light of Pellicano and Burr's (2012) theory of autism being associated with reduced priors. Although all the participants of this study were neurotypical, those with high AQ may have been expected to show less priming than those with low, if they relied less on historic prior information. It is hard to speculate why this did not occur; perhaps the proposed underuse of priors in autism does not extend to priming of attention. Or perhaps the effects do not extend to the neurotypical population with high AQ.

Most interestingly, the difference in pupillary response was strongly related to AQ, occurring only in individuals with low AQ. It is not clear exactly what drives this response, but as the difference was strongest for the switched trials, it seems reasonable to assume that it is the change in target color that drives increased pupillary dilation. This could be considered a "violation of perceptual expectation," much like the "odd-ball" p300 response that can be recorded by electroencephalography (Verleger & Śmigasiewicz, 2016). However, there are clear differences. Whereas P300 is strongest after a long series of similar trials followed by an "odd-ball", there was no measurable accumulation of the pupillary effect over sequences of trials. If the response relates to expectation (like mismatched negativity), then the expectation should increase with increased presentations of the same target color, as indeed does the reaction-time advantage. The "surprise" on color change should be greater after a long run of the same color, like mismatched negativity and also other odd-ball effects, such as increased apparent duration for odd-balls (Tse, Intriligator, Rivest, & Cavanagh, 2004). Rather than reflecting expectation violation, it is possible that the increased pupillary dilation on switching of target color is driven by the operation of resetting the target color. This operation must occur on every switch, irrespective of the length of the previous run, and would seem to be independent of the priming effects on attention.

We can only speculate on the connection between the increased pupillary response and AQ. It is highly unlikely that the pupillary response of high AQ individuals is damped or sluggish, as there was no dependency on AQ of pupil dilation to repeated trials (Figure 3C), nor is the baseline or response to button-press correlated with AQ. In addition, Turi et al. (2018) found no dependency of pupil dilation on AQ to switches in percept of a bistable illusion, showing that the pupillary response per se is intact. It would appear more likely that the difference in this experiment reflects the action of different mechanisms involved in reassigning the color driving the attentional search. It would be interesting to repeat the experiment with a group of clinically diagnosed autistic patients, to see if they behave like the neurotypicals with high AQ, or show different properties. The current study cautiously encourages the use of pupillometry in autism research. However, we do note the low internal

reliability of this measure (r = 0.35), which could prove limiting, possibly necessitating more trials and more participants.

This study supports an increasing body of evidence that pupillometry can be very useful in tracking perceptual processes, providing information that cannot be gathered from standard psychophysics. It would seem that these pupillometry measures may be more sensitive to variations in perceptual styles, and their dependency on personality traits.

Keywords: pupillometry, priming, reaction times, personality traits

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