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Atypical Attentional Effort During Visual Search in Autistic Adults: Evidence From Task-Evoked Pupillary Responses

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ABSTRACT

According to prevalent views, autistic individuals have a stronger tendency to allocate attention to details, as supported by reports of enhanced visual search performance. However, both the dynamics and the types of information involved in attentional guidance in autism are not fully understood. We addressed this issue by testing the influence of search history on visual search performance and pupil size in a long search display (Experiment 1) and on accuracy in a brief and masked—more attentionally demanding—search display (Experiment 2). Autistic ($N = 48$) and non-autistic ($N = 45$) participants searched for a color singleton target (all equiluminant colors) and responded by identifying its shape. In each trial, the target and distractor colors could be repeated, switched, or novel with respect to the previous trial. In Experiment 1, while overall reaction time was comparable across groups, the task-evoked pupillary responses (TEPRs) were smaller in the autistic group, indicating reduced attentional effort in autism. In Experiment 2, in a more attentionally demanding display, autistic individuals showed superior search accuracy. In both experiments, both groups showed a reliable effect of recent search history on performance, indicating that, similar to non-autistic individuals, autistic individuals rely on recent experience during attentional allocation. Alterations in attentional allocation and its interaction with recent experience in autism were reflected in pupil responses. These alterations may provide a sensitive marker of differences in the dynamics of attentional allocation in autism, which are reflected in behavioral measurements when display conditions are more attentionally demanding.

Sensory perception is a fundamental characteristic of autism and constitutes a core feature of the condition (reviewed by Robertson and Baron-Cohen 2017; Hadad and Yashar 2022). A prominent account proposes that perceptual alterations in autism stem from atypical attentional processes, particularly an increased tendency to allocate attention to local details (Robertson and Baron-Cohen 2017; Wang et al. 2015; but see Grubb et al. 2013). Consistent with this account, numerous studies have documented a visual search advantage in autism, and have further examined how different task characteristics influence search efficiency. Autistic individuals typically exhibit faster response times when identifying a target among distractors and demonstrate shallower search slopes as set size increases (e.g., Gonzalez et al. 2013; Milne et al. 2013; M. A. O'Riordan 2004; O'Riordan et al. 2001; Plaisted et al. 1998; Plaisted et al. 1998).

This advantage is especially robust in conjunction search tasks, in which the target is defined by a combination of two features, and the task is considered more attentionally demanding (Jarrold et al. 2005; Kaldy et al. 2011; M. O'Riordan 2000; O'Riordan et al. 2001; Plaisted et al. 1998). Enhanced performance has also been observed under more difficult search conditions (e.g., larger set sizes or high target–distractor similarity; Caron et al. 2006; Joseph et al. 2009; M. A. O'Riordan 2004; O'Riordan et al. 2001; Plaisted et al. 1998), and across different age groups and levels of symptom severity

(for review, see Kaldy et al. 2016). However, superior performance has also been reported in feature search tasks, particularly when target–distractor discriminability is low (O'Riordan et al. 2001).

At the same time, some studies failed to observe a search advantage, particularly when tasks involved social stimuli such as faces (Ashwin et al. 2006), brief stimulus presentations or crowding manipulations (Baldassi et al. 2009), or heterogeneous distractors and object-search paradigms (Riby et al. 2012). Overall, these findings suggest that visual search performance in autism is strongly influenced by task characteristics and attentional demands. Nevertheless, despite the popular belief in superior visual search performance, the mechanisms underlying this advantage remain unclear.

A growing body of research has turned to neurophysiological measures as indices of cognitive effort, attention, and arousal, with pupil size emerging as a particularly informative and non-invasive measure. Because pupil diameter is sensitive to both arousal and attentional demand, tasks requiring greater cognitive resources typically elicit larger task-evoked pupillary responses (TEPRs) than less demanding tasks (Einhäuser et al. 2008; Laeng et al. 2012; Partala and Surakka 2003; Mathôt and Vilotijević 2023). This sensitivity reflects the close coupling between pupil size and activity in the locus coeruleus–norepinephrine (LC–NE) system (Sara 2009), which plays a central role in regulating arousal, attentional orienting, and cognitive effort (Sara and Bouret 2012; Kaldy et al. 2016; Bast et al. 2018; Kim et al. 2022). Within this framework, baseline pupil diameter is thought to index tonic LC–NE activity—reflecting sustained arousal and attentional state—whereas stimulus-locked TEPRs reflect phasic LC–NE responses to behaviorally relevant events (Aston-Jones and Cohen 2005; Bast et al. 2018; Kim et al. 2022). Notably, moderate tonic LC–NE activity is believed to support optimal task engagement and selective attention, whereas elevated tonic activity may broaden sensitivity to environmental stimuli at the cost of attentional stability (Bast et al. 2018). Consistent with this account, several studies have reported enlarged baseline pupil diameter in autistic children (Anderson et al. 2006, 2013; Anderson and Colombo 2009; Bast et al. 2025), and Keehn et al. (2023) further linked this elevated tonic arousal to accelerated visual search performance, suggesting that upregulation of the LC–NE system may contribute to enhanced perceptual selectivity in autism.

Evidence concerning phasic pupil responses, however, has been less consistent, with findings appearing to depend on both developmental stage and task demands. Some studies have reported enhanced TEPRs during perceptual and visual search tasks in young autistic children (Blaser et al. 2014; Kim et al. 2022), whereas Zhao et al. (2022) found attenuated TEPRs to surprising auditory events, pointing to atypical attentional orienting under conditions of violated expectation.

Importantly, TEPR is also strongly influenced by luminance. Because luminance was not controlled in the study by Blaser et al. (2014), it remains unclear whether the observed group differences in pupil responses reflect differences in cognitive effort or sensitivity to luminance changes. Moreover, as most of the studies focused on children and toddlers, developmental factors and compensatory strategies may limit the generalizability of these findings to autistic adults, as has been demonstrated in other domains (e.g., the McGurk effect; Taylor and Seltzer 2010). Given the limited literature examining pupil dilation base-line and TEPR during luminance-controlled visual search tasks in autistic adults, the present study aimed to address this gap.

In the present study, we address these issues by examining visual search performance—measured by response time (RT) and accuracy—together with TEPRs during a color singleton search task in autistic and non-autistic adults. To minimize luminance-driven pupil responses, all displays were composed of isoluminant colors presented on equiluminant backgrounds. Beyond overall performance, we also examined the effect of search history. Recent experience is a key determinant of attentional guidance: in visual search tasks, responses are typically faster and more accurate when the target-defining feature repeats across trials than when it changes. This phenomenon, known as "priming of pop-out" or "intertrial priming," reflects the influence of prior experience on attentional selection (Campana et al. 2008; Á. Kristjánsson 2006; A. Kristjánsson 2009; Kristjánsson and Driver 2008; Lamy and Kristjánsson 2013; Maljkovic and Nakayama 1994, 1996; Yashar and Lamy 2010a, 2010b, 2011; Yashar et al. 2017). Forty-five non-autistic and 48 autistic individuals performed visual search tasks for color singleton targets (Experiments 1 and 2). On each trial, target and distractor colors were randomly selected from four possible equiluminant colors, creating conditions in which colors were repeated, novel, or switched relative to the previous trial. In Experiment 1, while RT performance level and intertrial priming were comparable across groups, analysis of TEPRs revealed differences in task-related effort. In Experiment 2, under more perceptually demanding conditions, performance level was higher in the autistic group compared to the non-autistic group.

1 | Experiment 1: Search Time and Pupillometry

1.1 | Method

1.1.1 | Participants

Thirty-two neurotypical students (non-autistic group) from the University of Haifa (21 females; age range: 18–39 years) and 34 individuals (autistic group) diagnosed with Autism Spectrum Disorder (ASD) according to DSM-5 standards (American Psychiatric Association 2013; 8 females; age range: 18–39 years) participated in the study. Full sample characteristics prior to exclusions are provided in the Supporting Information file (Table S1). All participants in the autistic group had a prior clinical diagnosis of autism spectrum disorder provided by a licensed psychiatrist or clinical psychologist. To further characterize the sample, all participants underwent assessment using the Autism Diagnostic Observation Schedule (ADOS), administered by a research assistant who was formally trained and certified in its administration.

All participants were native Hebrew speakers with normal or corrected-to-normal vision and no color blindness, as confirmed by the Ishihara Color Vision Test (Ishihara 1918). Note that although the group varied in the ratio of male and female,

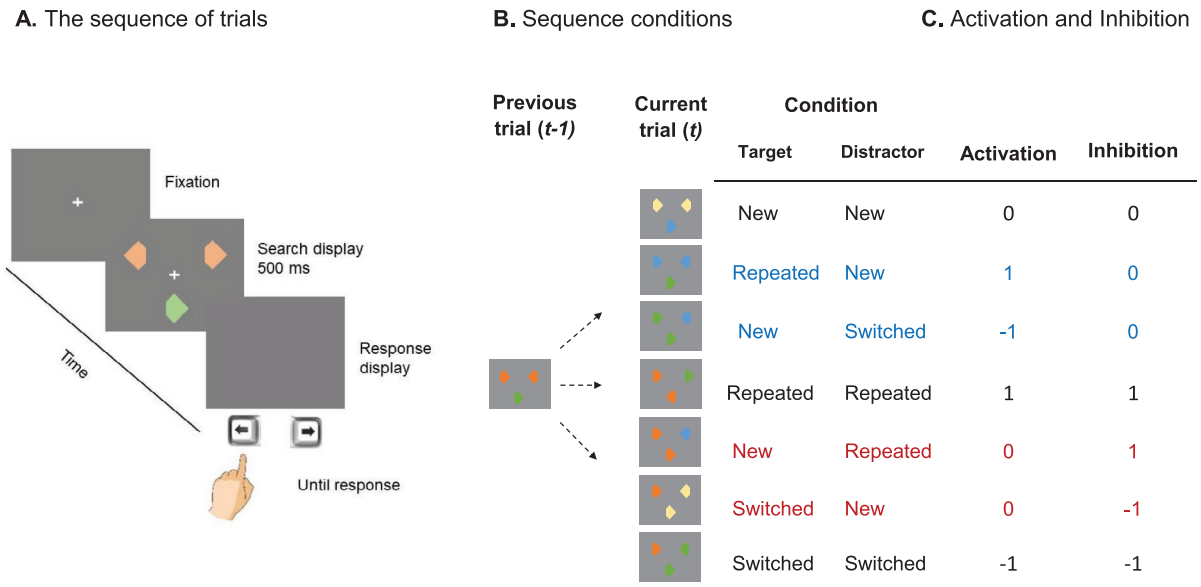

FIGURE 1 | (A) Sequence of trials for Experiment 1. The target is the diamond with a unique color, and the two homogeneous diamonds are the distractors. (B) Sample displays corresponding to the seven possible trial sequence types in Experiments 1 and 2. Illustration of possible variations in target and distractor colors between the previous and the current trial. The term "Repeated" is used when a color is repeated from the previous trial, "New"- when a color is not present in the previous trial, and "Switched"- when a color is repeated from the previous trial but takes on the alternative color role (target or distractor). Here, (*t*−1) refers to the previous trial, while (*t*) refers to the current trial. (C) The mechanism of target activation and distractor inhibition. Target activation is defined as the benefit of repeating the target color and the cost of switching a distractor color from the previous trial (target color in the previous trial becomes distractor color in the current trial). Distractor inhibition is defined as the benefit of repeating the distractor color and the cost of switching a target color from the previous trial. Activation and inhibition indices take values of +1 (benefit), 0 (baseline), or −1 (cost).

there is no indication of sex differences in performance and pupil response in the visual search task (Aboyoun and Dabbs 1998; Bradley et al. 2008; Dong et al. 2020). Written informed consent was obtained from all participants, who received either course credit or monetary compensation (120 NIS, approximately $34) for their participation. The study was approved by the University of Haifa Institutional Review Board for Human Participants in Research (Approval No. 373/18).

1.1.2 | Apparatus

The participants were seated in a dimly lit room. We set the viewing distance at 57 cm by using a chinrest. Stimuli (visual presentations) were produced using Matlab (r2019b, The Mathworks Inc., Natic, MA), with the psychophysics Toolbox extensions, and presented on a VIEWPixx calibrated monitor (with 1920×1200 resolution and 120-Hz; VPixx Technologies Inc. Ltd Canada). We used a SpectroCAL MKII (Cambridge Research Systems, UK) spectroradiometer to calibrate luminance and color. Eye movement and pupil size (diameter) were monitored at 500 Hz with a camera mounted below the screen (Eye Link 1000 plus, SR Research).

1.1.3 | Stimuli and Procedure

All stimuli were presented on a gray background. Each trial began with a white fixation cross (plus sign) 0.2×0.2 degrees of visual angle (dva) at the center of the gray screen for 500 ms. Following the participant's fixation for at least 300 ms, a search display appeared on the screen, and participants must keep fixation until the stimuli display disappeared from the screen. The search display consists of three colored diamonds, 1.0×1.0 (dva), with a 0.15 cut-off corner on either the left or right side. One of the diamonds is the target with a unique color, while the other two are uniformly colored distractors. The hues of the diamonds were chosen randomly from four options and were selected from 48 isoluminant colors in the DKL color space (Chetverikov et al. 2017a, 2017b; Hansmann-Roth et al. 2019). The search elements were evenly spread on an imaginary circle at angles of (0°, 120°, 240°) from horizontal with 4.5 dva eccentricity. Stimuli and background were equiluminant (range 46.7–51.35 cd/m^2).

Participants were instructed to find a diamond that had a different color than the others and indicate its shape (whether it was cut off on the left or right side) by pressing the arrow key on their keyboard. Participants were instructed to respond as fast and accurately as possible. The search display appeared on the screen until the participant made a response. Following the participant response, the next trial begins after a randomly intertrial interval (ITI) ranging from 400 to 600 ms, increasing in 10 ms increments after the appearance of a fixation cross. After each response, feedback was given as a short or long frequency sound for a correct or incorrect answer (Figure 1A displays an example of the stimulus displays).

During the behavioral task, the participants' eye tracking data was recorded; participants were required to maintain fixation on the cross. Any trials in which fixation was broken were excluded, and additional trials were completed instead.

1.1.4 | Design and Analysis

Participants completed 10 experimental blocks, each consisting of 56 trials, for a total of 560 trials. Before the main experiment, a short training phase of 20 trials familiarized participants with the task to ensure proper understanding and performance.

1.1.5 | Sequence Conditions

The target and distractor colors were randomly selected from four available colors with the restriction that target color and distractor color could not be the same (Yashar and Lamy 2010a). During each trial, the target color could be target repeated color (same as the previous target color), target switched color (same as the previous distractor color), or target new color (target color did not appear in the previous trial). Similarly, three types of sequences were defined by distractor variation in consecutive trials: in each trial, the distractor color could either be repeated, switched, or new. A random selection of the target and distractor colors on each trial led to seven possible combinations. Figure 1B illustrates the different types of trial sequences that could occur (the two conditions of "switched target–repeated distractor" and "repeated target–switched distractor" cannot occur). The basic intertrial repetition effect (Maljkovic and Nakayama 1994) can be observed by comparing repeated-target/repeated-distractor trials with switched-target/switched-distractor trials.

1.1.6 | Activation and Inhibition Indexes

To isolate the contributions of priming by target color in previous trial ("activation") and priming by distractor color in the previous trial ("inhibition") we created two trial-wise indices following Lamy et al. (2008) and Yashar and Lamy et al. (2010). Both activation and inhibition indexes could take a value from +1 (benefit, in repeated role trials), 0 (baseline, in new trials) and −1 (cost, in switched role trials) (see Figure 1C). These indices were entered as continuous predictors in our linear mixed-effects models of RT, accuracy, and pupil size.

1.1.7 | Analysis

All analyses were done in the statistical software R (v 4.4.0; R Core Team 2024) with additional packages. For reading raw eye-tracking data and processing pupil size data, we used the gazeR package, while blink detection was accomplished with the saccades package (Geller et al. 2020; Engbert and Kliegl 2003).

For the pupil size and behavioral analyses, we fitted linear mixed-effects models (LMEMs) and generalized linear mixed-effects models (GLMMs) using the lme4 package (Bates et al. 2012). In models, we included group (autistic vs. non-autistic) as a between-subjects fixed effect, and repetition conditions as a within-subject fixed effect, while subjects and condition slope as random effects. Pairwise comparisons were conducted using the emmeans package (v1.10.2; Lenth 2024).

1.1.8 | Pupillometry Data Pre-Processing

To ensure accurate interpolation, we extended the time window around each blink to ensure accurate interpolation. Specifically, interpolation began 100 ms before and continued for 100 ms after each blink. Given that the eye tracker sampled at 500 Hz (one sample every 2 ms), this approach allowed us to capture subtle changes in pupil size surrounding blink events. To address missing data resulting from blinks or eye tracker failures, we applied a 5-point moving average ($n = 5$) for smoothing and interpolation at the 500 Hz sampling rate. Mean baseline pupil activity was indexed by pupil size during the 100 ms pre-stimulus interval (50 samples at 500 Hz). Baseline pupil size was calculated for each participant by averaging pupil samples within this interval. To calculate TEPR, for each trial, the mean pupil size during this baseline window was subtracted from all subsequent samples, yielding a baseline-normalized pupil trace. Trials containing more than 20% missing pupil samples were excluded from further analysis.

For the behavioral analysis, we used LMEM, GLMM, and sampled *t*-tests. Sequence conditions and group were considered within-participant factors, with RT or accuracy percentage as the dependent variables. Degrees of freedom in the LMEM and GLMM correspond to the number of estimated parameters in the model.

1.2 | Results and Discussion

Three autistic participants did not complete the experiment. Data from four autistic and two non-autistic participants were excluded due to low accuracy (below 60%). Trials with fixation breaks were excluded from analysis. For pupil size and RT analysis, we removed trials with incorrect responses or RTs more than three standard deviations from the mean. Table 1 presents descriptive statistics for participant characteristics in the final sample after exclusions (see Section 4 for details).

The two groups did not differ significantly in age, $t(60.7) = -0.08$, $p = 0.93$. Additionally, participants completed the non-verbal intelligence test, assessed using the Test of Nonverbal Intelligence (TONI, 4th edition) and the Self-Administered Autism Quotient (AQ) questionnaire. A *t*-test showed a significantly higher AQ for the autistic group compared to the non-autistic group, $t(60) = 6.93$,

TABLE 1 | Descriptive statistics of participant characteristics by group for Experiment 1 (for the final sample after the exclusions).

	Autistic	Non-autistic
N	27	30
Gender	(8 females/19 males)	(20 females/10 males)
Age	26.7 (7.5)	27.4 (7.12)
AQ Score	30.4 (8.31)	15.9 (6.9)
TONI Score	104.04 (12.74)	106.3 (7.31)

Note: Standard errors are given in parentheses.
Abbreviations: AQ = Autistic Quotient; TONI = Test of Nonverbal Intelligence.

$p < 0.001$, Cohen's $d = 1.75$. In contrast, there was no significant group difference in TONI scores, $t(57.66) = -0.36$, $p = 0.71$.

1.2.1 | Trial Exclusion

1.2.1.1 | RT. Trials with RTs exceeding ±3 SDs from the participant mean were excluded (0.63%, SD = 1.2 in the autistic group; 0.36%, SD = 0.47 in the non-autistic group). The proportion of excluded trials did not differ significantly between groups, $t(33.19) = 1.08$, $p = 0.29$, indicating comparable exclusion rates across groups.

1.2.1.2 | Fixation Breaks. Trials with fixation breaks were excluded (11.91%, SD = 15.8 in the autistic group; 8.41%, SD = 10.8 in the non-autistic group). The proportion of excluded trials did not differ significantly between groups, $t(45.27) = 0.97$, $p = 0.34$, indicating comparable fixation performance across groups.

1.2.2 | The Basic Feature Priming Effect

To examine the effects of feature priming on RT, we conducted LMEM analysis with repetition condition (repeated target—repeated distractor vs. switched target—switched distractor) and group as fixed effects, and subject intercepts and slopes for condition as random effects.

1.2.2.1 | RT. Figure 2 depicts mean RTs as a function of group and trials in which both target and distractors were either repeated or switched. First, autistic individuals did not show superior search speed, as the main effect of group was not significant, $\beta = -31.26$ ms, $t = -0.82$, $p = 0.42$, $\eta p^2 = 0.006$. The results demonstrate the basic intertrial repetition effect, that is, participants responded faster when the target and distractor colors were repeated rather than switched. as indicated by the significant main effect of repetition, $\beta = 45.22$ ms, $t = 6.16$, $p < 0.001$, $\eta p^2 = 0.03$. There was a significant interaction between sequence condition and group, $t = 1.93$, $p = 0.05$, $\eta p^2 < 0.001$, suggesting that the RT increase from repeated to switched trials was slightly larger for non-autistic participants. Simple effects analyses confirmed a significant repetition effect in both groups (autistic: $t = 6.61$, $p < 0.001$; non-autistic: $t = 9.01$, $p < 0.001$).

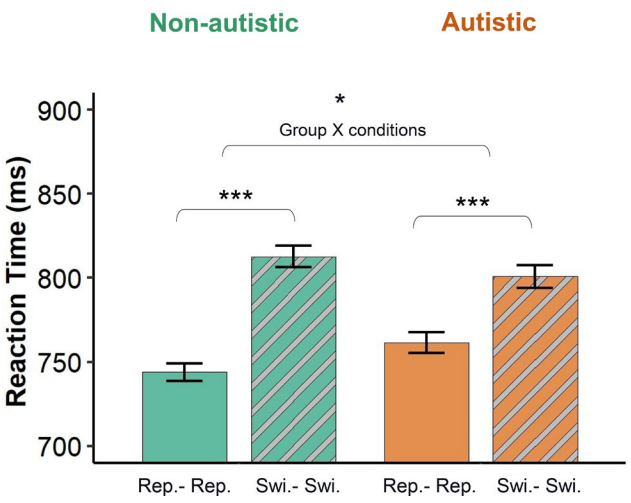

FIGURE 2 | Difference between autistic and non-autistic groups in the effect of feature priming. The graph displays the RT data on two sequence conditions: Rep.–Rep.: repeated target–repeated distractor colors, Swi.–Swi.: switched target–switched distractor colors. *$p < 0.05$, ***$p < 0.001$.

Overall, both groups exhibited a basic feature priming effect: participants responded faster and more efficiently when target and distractor colors were repeated. There is marginal evidence that this effect differed subtly between autistic and non-autistic participants (see Figure 2). Accuracy results are consistent with the RT results and rule out speed-accuracy trade-off effects (see Supporting Information and Table S3).

1.2.2.2 | TEPR. Figure 3A illustrates the mean base-line pupil activity, indexed by baseline pupil size expressed in arbitrary units (a.u.) during the final 100 ms before stimulus onset. A Welch two-sample *t*-test revealed no difference in baseline pupil size between autistic and non-autistic participants, $t(23.67) = -0.24$, $p = 0.81$. Figure 3B illustrates TEPRs for repeated and switched trials in both the autistic and non-autistic groups. The LME model included time since stimulus onset (in ms), condition (repeated colors vs. switched colors), and group as fixed effects and included intercepts for subjects and conditions, as well as random slopes of subjects and conditions (see Supporting Information and Table S4).

The analysis showed a significant main effect of time, $\beta = 3.98$, $t = 85.52$, $p < 0.001$, $\eta p^2 = 0.50$, indicating a TEPR characterized by increasing pupil size following stimulus presentation (Figure 3B). TEPR was modulated by the basic priming effect, as reflected by a significant interaction between time and condition, $t = 4.50$, $p < 0.001$, $\eta p^2 = 0.001$. Importantly, the overall phasic TEPR was affected by group, as reflected by a significant interaction between time and group, $t = 57.21$, $p < 0.001$, $\eta p^2 = 0.08$, with larger TEPRs observed in the non-autistic group compared with the autistic group. Besides the TEPR, overall pupil size during the trial was not affected by condition or group, as neither the main effect of condition nor the main effect of group was significant ($\beta = -3.19$, $t = -0.95$, $p = 0.35$, $\eta p^2 = 0.05$; $\beta = -3.63$, $t = -0.42$, $p = 0.68$, $\eta p^2 = 0.004$, respectively).

Critically, although there was no significant interaction between condition and group, $t = -0.1$, $p = 0.91$, $\eta p^2 < 0.001$, the three-way interaction between time, condition, and group was significant, $t = 2.48$, $p < 0.01$, $\eta p^2 < 0.001$, indicating differences in the dynamics of the feature priming effect on TEPR between autistic and non-autistic participants.

Next, we performed pairwise comparisons using model-predicted estimated marginal means to directly assess group differences in pupillary responses. The analyses revealed differences between autistic and non-autistic participants in both repetition conditions. In the repeated condition, significant group differences first appeared at 720 ms and remained reliable through 1600 ms (all $p < 0.01$). In the switched condition, group differences emerged slightly later, beginning at 800 ms and persisting until 1600 ms (all $p < 0.01$). Across both conditions,

autistic participants showed reduced pupil dilation compared with non-autistic participants. These findings indicate sustained, time-dependent group differences in TEPR across both repetition conditions (Figure 3B).

Figure 3C illustrates the delta of TEPR (ΔTEPR) as a function of group and repetition effect, which was calculated by subtracting the pupil size of repeated trials from that of switched trials. TEPR in autistic individuals showed an overall monotonic increase compared to non-autistic individuals, who exhibited a more pronounced dilation at a later stage (see Supporting Information and Table S5).

1.2.3 | Activation and Inhibition, Cost and Benefit

To test the separate contributions of activation and inhibition, we included trials in which either no color reappeared (new target and new distractor colors) or only one color reappeared. Table S2 in the SI file shows the mean accuracy and RT for each of these five conditions. We then calculated activation and inhibition indexes as described in the Section 1.1.5.

1.2.3.1 | RT. Figure 4 depicts mean RTs as a function of group and activation and inhibition index. To examine the independent contributions of target-color activation and distractor-color inhibition

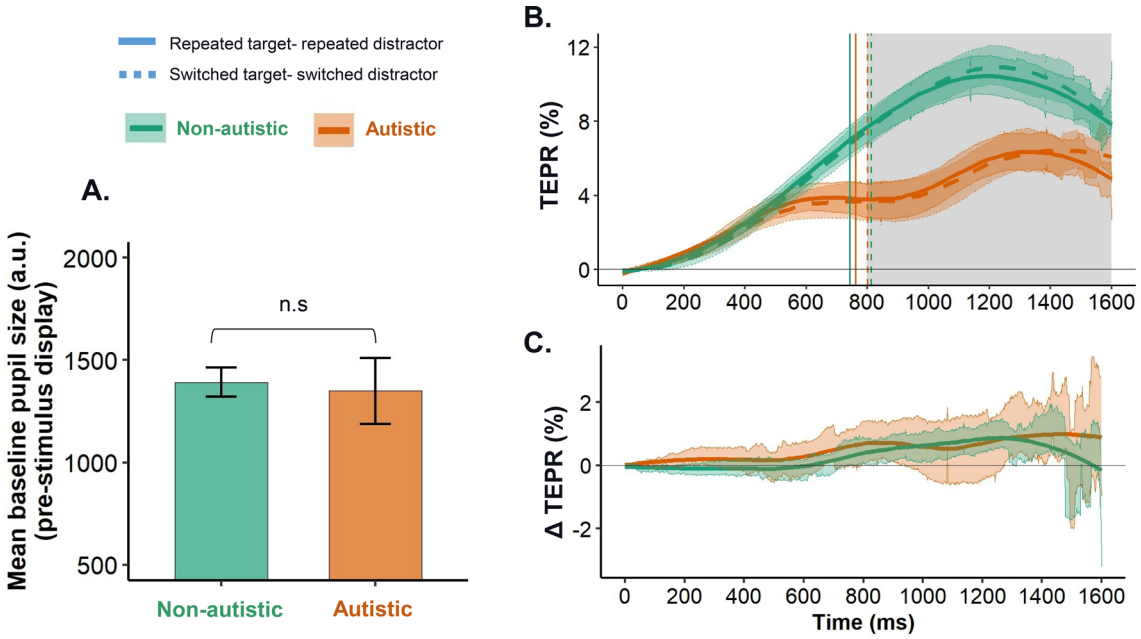

FIGURE 3 | Pupil baseline and TEPR as a function of color repetition and group. (A) Mean baseline pupil activity, indexed by baseline pupil size during the final 100 ms before stimulus display for autistic and non-autistic participants. (B) TEPR for trials in which target and distractor colors were repeated versus switched. Vertical lines represent the mean reaction time (RT) for each group across both conditions. The gray shaded region marks the time periods where the group difference is statistically significant at each time point ($p < 0.01$). (C) Group differences in TEPR (ΔTEPR), computed by subtracting responses for trials where both target and distractor colors were repeated from those where both were switched. Shaded ribbons represent ±1 SEM.

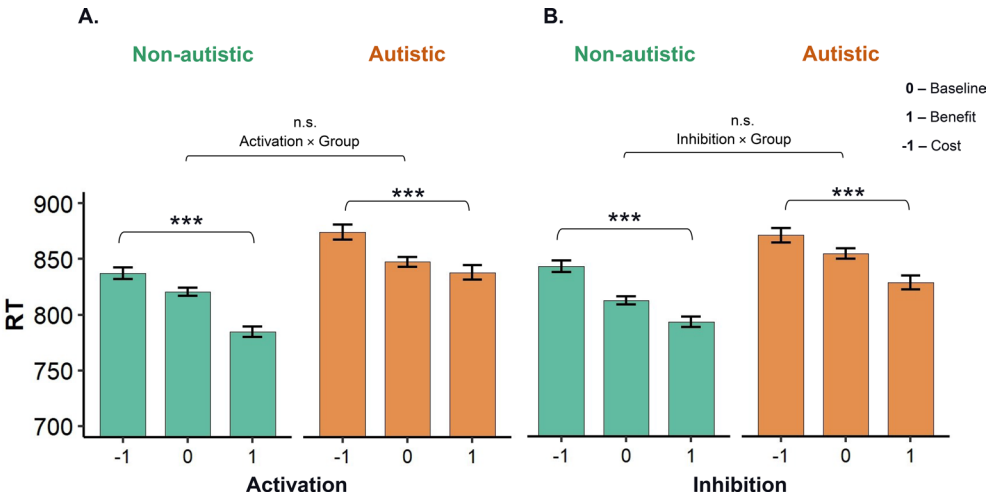

FIGURE 4 | Activation and inhibition effect on RT. RT as a function of target activation (A) and distractor inhibition (B) between autistic and non-autistic groups in RT. ***$p < 0.001$.

on, we fitted a linear mixed-effects model predicting trial-level RT with fixed effects of activation, group, and all two- and three-way interactions ($N = 19{,}914$ trials; ML estimation).

Results showed significant linear benefits for distractor-color inhibition and target-color activation. Each one-unit increase in the inhibition index was associated with a 13.13 ms decrease in RT, $t = -3.77$, $p < 0.001$, $\eta p^2 = 0.43$. Likewise, target-color activation produced a significant benefit of 10.09 ms per activation unit, $t = -3.11$, $p = 0.002$, $\eta p^2 = 0.33$. All other effects were not significant. Namely, there was no significant main effect of group, $t = -0.87$, $p = 0.38$, $\eta p^2 = 0.01$ nor were any interactions significant: group × inhibition, $t = -0.58$, $p = 0.56$, $\eta p^2 = 0.02$; group × activation, $t = -1.01$, $p = 0.31$, $\eta p^2 = 0.008$; activation × inhibition, $t = 0.78$, $p = 0.43$, $\eta p^2 < 0.001$; and group × activation × inhibition, $t = 0.19$, $p = 0.84$, $\eta p^2 < 0.001$. Thus, autistic and non-autistic participants exhibited comparable activation and inhibition benefits on RT. Analysis of accuracy confirmed no speed accuracy tradeoffs in activation inhibition effects (Supporting Information and Figure S1 in the SI file).

1.2.3.2 | TEPR. Similar to the RT and accuracy analyses, we examined activation and inhibition benefits and costs on TEPR. A complete description of the LME analysis is provided in Supporting Information and Figure S2 in the SI file.

The results of Experiment 1 demonstrate that autistic and non-autistic individuals exhibit comparable search speed and accuracy, as well as similar intertrial repetition effects on performance. Although there was a group × color repetition interaction on RT and pupil size, the repetition effect was reliable in both groups, and no substantial differences were found in activation and inhibition indexes across groups.

While these findings differ from some previous reports of visual search superiority in autism (Constable et al. 2010; Milne et al. 2013; M. A. O'Riordan 2004; Plaisted et al. 1998), they align with studies showing no such advantage (Ashwin et al. 2006; Baldassi et al. 2009; Riby et al. 2012). Notably, our results reveal differences in TEPR between groups, with significant three-way interactions involving time, condition, and group, and a significant two-way interaction between time and group. Importantly, when both colors were repeated or switched, and when only one color reappeared from the previous trial, autistic participants showed reduced TEPR. Thus, even when behavioral performance is highly similar, pupil dilation reveals differences in underlying processing between groups. To further examine whether comparable performance across groups reflects differences in task demand, we conducted Experiment 2.

2 | Experiment 2: Early Processing of Search

RTs measurements in intertrial priming in visual search reflect multi-stages of processing (Lamy et al. 2010; Yashar and Lamy 2011), including perceptual and attentional selection (Yashar and Lamy 2010b; Yashar et al. 2017) as well as motor response (Yashar and Lamy 2011). Thus, it is unclear whether the lack of group differences in RT reflects processing and strategies at the level of response that compensate for group differences at the perceptual level. Furthermore, to focus on search speed and RT, the accuracy performance in Experiment 1 was very high and may not be sensitive to perceptual differences. Hence, it is unknown whether the differences in the TEPR across groups will be reflected in performance under more demanding perceptual conditions. To address this, in Experiment 2 we presented the search display briefly, followed by a visual mask while measuring accuracy alone with no speed stress. This allows us to measure perceptual performance while minimizing the influence of response strategies. To maintain accurate performance at sensitive levels, stimulus onset asynchrony (SOA) between the search display and the following mask was set at a threshold level for each participant using a staircase procedure.

3 | Method

3.1 | Participants

Twenty-three neurotypical students (non-autistic group) from the University of Haifa (15 females, age range: 18–39 years) and 27 participants (autistic group) diagnosed with Autism Spectrum Disorder (5 females aged 18–39 years) were included in this Experiment. Full sample characteristics prior to exclusions are provided in the SI file (Table S1).

3.2 | Stimuli and Procedure

The stimuli and procedure were identical to those used in Experiment 1, with a few modifications. Stimuli were presented for 100 ms, followed by a 500 ms mask display composed of three 5 × 5 grids of small colored squares (0.3 × 0.3 dva) positioned in the same locations as the diamonds. To reduce the likelihood of speed–accuracy trade-offs, participants were instructed to wait 500 ms until a plus sign appeared on a gray screen before responding (see Figure 5).

3.3 | Procedure

As in Experiment 1, participants searched for the color singleton and discriminated the orientation of its shape by pressing the arrow key on the keyboard as accurately as possible with no speed stress. The Experiment began with a brief training session consisting of 25 trials.

3.3.1 | Phase 1: Threshold Procedure

We estimated the threshold SOA between the search display and the mask for each participant by using a QUEST adaptive staircase procedure (Kingdom and Prins 2010).

QUEST is an adaptive Bayesian psychometric procedure used to estimate perceptual thresholds efficiently across psychophysical trials (Watson and Pelli 1983). Following each response, the algorithm updates the posterior probability distribution of the threshold estimate based on prior assumptions and previous responses. The stimulus level for the next trial is then selected

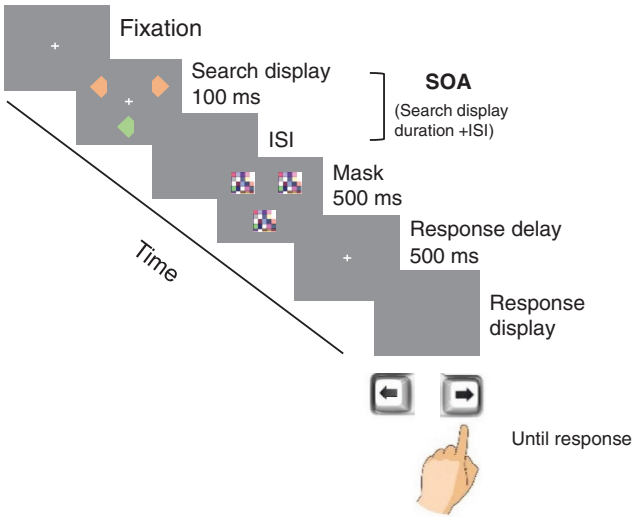

FIGURE 5 | An illustration of the stimuli and the sequence of events within a trial in Experiment 2. The ISI between the stimulus and the mask was individually determined by a staircase procedure at threshold levels. The SOA is computed by adding the search display duration to the ISI threshold.

according to the most probable current threshold estimate (Watson 2017). The SOA threshold obtained at the end of this phase was used for all subsequent experimental blocks.

3.3.2 | Phase 2: The Experimental Session

Following threshold estimation, participants completed a total of 480 trials, such that the minimum number of trials in a repetition condition was 68.

4 | Results and Discussion

Data from nine autistic participants and two non-autistic participants were excluded due to low accuracy levels in phase 2. Hence, the results are based on data collected from 18 autistics and 21 non-autistic participants. The two groups did not differ significantly in age, t (30.90) = 0.50, $p = 0.62$. However, the autistic group exhibited significantly higher scores on the AQ compared to the non-autistic group, t (39.63) = 7.65, $p < 0.001$, Cohen's $d = 2.36$. While there was no significant difference between groups in the TONI scores, t (32.22) = −0.02, $p = 0.97$.

Table 2 presents descriptive statistics for participant characteristics in the final sample after exclusions.

4.1 | SOA Threshold

Figure 6 presents the SOA thresholds between the two groups. A two-sample t-test revealed a significant difference in SOA thresholds between the two groups, t (37) = 2.03, $p = 0.049$, Cohen's $d = 0.63$, where non-autistic participants showed higher thresholds than autistic participants (Figure 6).

TABLE 2 | Descriptive statistics of participant characteristics by group for experiment 2.

	Autistic	Non-autistic
N	18	21
Gender	(5 females/13 males)	(15 females/6 males)
Age	26.6 (7.79)	27.7 (5.76)
AQ Score	31.23 (6.92)	15.61 (6.21)
TONI Score	105.09 (13.4)	105.19 (7.57)

Note: Standard errors are given in parentheses. AQ = Autistic Quotient; TONI = Test of Nonverbal Intelligence.

4.2 | The Basic Feature Priming Effect

Figure 7 presents the accuracy data for the two main trial sequence conditions as a function of group. A GLM model with a binomial distribution revealed a significant main effect of group, $z = 2.34$, $p = 0.019$, $\eta p^2 = 0.001$, indicating that autistic participants were overall more accurate than non-autistic participants. A significant main effect of condition was also observed, $z = -2.23$, $p = 0.025$, $\eta p^2 = 0.005$, with higher accuracy in repeated compared to switched trials, confirming a feature priming effect across groups. No significant group × condition interaction was found, $z = -1.17$, $p = 0.24$, $\eta p^2 < 0.001$. A similar pattern of results was observed in the accuracy analyses of the activation and inhibition indices. Specifically, although there were main effects of group and inhibition, no significant interactions were found between group and either the inhibition or activation indices (see Supporting Information, Figure S3, and Table S6 in SI file).

The results of Experiment 2 show an overall performance difference between autistic and non-autistic individuals when accuracy is measured in a briefly masked display, that is, when the presentation is perceptually demanding. These findings suggest that the differences in the TEPRs found in Experiment 1 may be associated with differences in perceptual processing in the autistic population. Consistent with Experiment 1, both groups showed reliable effect of intertrial repetition on accuracy in Experiment 2.

5 | General Discussion

By measuring response times, task-evoked pupillary responses (TEPRs), and accuracy across two experiments, the present study elucidated multiple aspects of the attentional guidance advantage in autism during visual search with isoluminant stimuli. Although intertrial repetition effects were comparable across groups, TEPR analyses revealed group differences in the temporal dynamics of search effort. We propose that the reduced effort allocated during extended search in Experiment 1 reflects a more efficient attentional guidance process in autism—one that may preserve cognitive resources available for perceptual processing under higher task demands. Consistent with this account, autistic participants showed higher perceptual accuracy in Experiment 2, where the same search display was presented

under more demanding visual conditions (i.e., masked brief presentation).

5.1 | A Typical Intertrial Priming Effect on Visual Search Performance in Autism

Consistent with prior literature involving non-autistic participants (Kristjánsson and Driver 2008; Maljkovic and Nakayama 1994, 1996; Lamy et al. 2008, 2011; Yashar and Lamy 2010b), both groups showed reliable intertrial repetition effects. Despite the interaction between group and intertrial repetition on RT and the time course of TEPR in Experiment 1, no such interaction was found for accuracy in Experiment 2, and the autistic group showed significant repetition effects in all measurements. Furthermore, intertrial inhibition and activation interaction effects on RT or accuracy were comparable across groups.

Thus, these findings suggest that autistic individuals rely on recent search history during color singleton search. This finding aligns with a previous study examining autistic traits in non-autistic populations (Pomè et al. 2020) and is consistent with recent work showing typical use of prior information in autism (Fazioli et al. 2025).

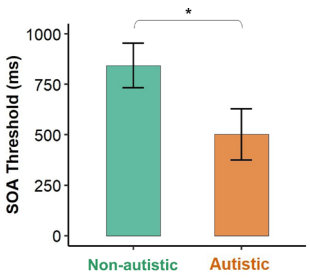

FIGURE 6 | SOA thresholds between autistic and non-autistic groups. The SOA represents the sum of the search display duration (100 ms) and the individual ISI. *$p < 0.05$.

5.2 | Visual Search Advantage in Autism

Previous research suggests that individuals with autism often exhibit an advantage in visual search, typically demonstrating faster RTs than non-autistic individuals (Plaisted et al. 1998; Milne et al. 2013; M. A. O'Riordan 2004). However, some studies have failed to observe this superiority. For example, Baldassi et al. (2009) reported no significant group differences in orientation discrimination during visual search. Here, on the one hand, in Experiment 1—with a long display duration—autistic individuals did not show faster RTs. Yet, their superiority may be exhibited by reduced effort, as suggested by their diminished TEPR. On the other hand, however, under more perceptually demanding conditions, autistic participants trend toward shorter inter-stimulus intervals (ISIs) and show higher accuracy in Experiment 2. These findings underscore the importance of selecting appropriate measurement modalities when assessing group differences. Relying on RTs alone may not adequately capture processing speed, particularly when differences in cognitive effort offset performance benefits. By measuring pupil size in Experiment 1 and perceptual speed and accuracy in Experiment 2, we were able to demonstrate that autistic superiority in visual search may stem from early stages of perceptual processing.

5.3 | Alterations in Task-Evoked Pupil Response in Autism

Task-evoked pupillary responses are linked to the LC–NE system, which supports a wide range of cognitive processes, including visual attention (Huang and Clewett 2024). In autism, TEPRs to auditory oddball stimuli have been reported as reduced relative to non-autistic individuals, a pattern interpreted as reflecting atypical dynamic allocation of attention mediated by the LC–NE system (Zhao et al. 2022). However, that study did not include behavioral measures, leaving it unclear how these pupillometric differences relate to attentional performance. The current results extend this picture by revealing group differences

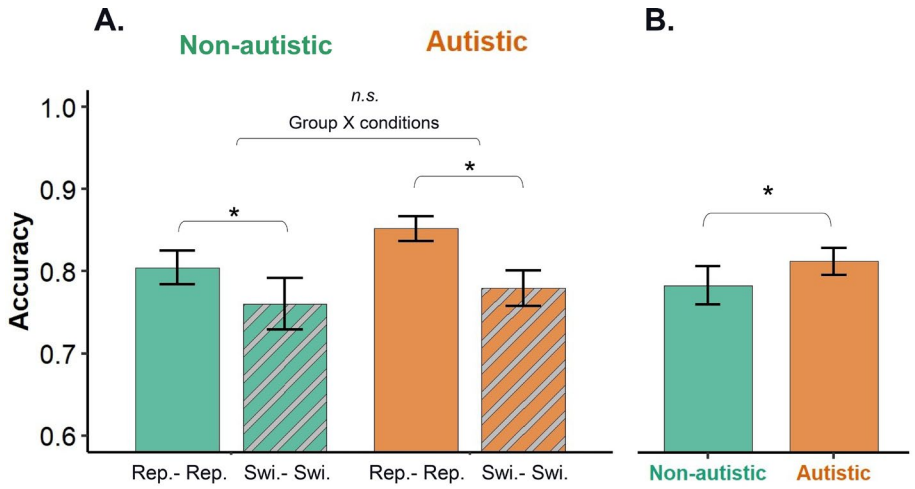

FIGURE 7 | Accuracy comparison between autistic and non-autistic groups in the effect of feature priming (Experiment 2). Panel (A) displays the accuracy data on two sequence conditions: Rep.–Rep. (repeated target and repeated distractor colors) and Swi.–Swi. (switched target and switched distractor colors). Panel (B) shows the main effect of group on accuracy. *$p < 0.05$.

in TEPR across several dimensions—most notably, an overall reduction in task-evoked pupil dilation during color singleton search in autistic adults.

Importantly, this pattern differs from studies in autistic toddlers and children reporting enlarged baseline pupil diameter and enhanced TEPRs during visual search tasks (Anderson et al. 2006, 2013; Anderson and Colombo 2009; Blaser et al. 2014; Keehn et al. 2023). In the current adult sample, no group differences were observed in baseline pupil diameter, whereas autistic adults exhibited reduced TEPRs relative to non-autistic adults. This dissociation may reflect developmental changes in LC–NE functioning across the lifespan. Previous accounts have proposed that elevated tonic arousal in autism may normalize or become compensated for with age, while atypical phasic attentional modulation persists into adulthood (Bast et al. 2018). Consistent with this view, Martineau et al. (2011) reported typical baseline pupil diameter in older autistic children alongside continued alterations in stimulus-locked pupil responses to socially relevant stimuli. The present findings extend this developmental pattern to visual search in autistic adults, suggesting that atypical phasic pupillary modulation may persist even in the absence of altered tonic arousal.

Reduced TEPRs in the current study may therefore reflect differences in the temporal dynamics of attentional allocation, adaptive regulation of cognitive effort, or perceptual processing strategies during task performance (Aston-Jones and Cohen 2005; Sara and Bouret 2012)—rather than generalized tonic hyperarousal. Critically, these group differences in pupillary response were not accompanied by performance costs: overall reaction times and intertrial repetition effects were largely comparable across groups, and autistic participants showed a clear accuracy advantage under brief, masked display conditions. Together, these findings suggest that atypical phasic pupillometric responses do not necessarily index impaired attentional functioning. Rather, altered pupillary dynamics may reflect qualitative differences in attentional regulation or information-processing strategies—ones that, in the context of visual search, appear compatible with preserved or even superior task performance.

5.4 | Limitations

In Experiment 1, TEPRs were measured during a long display duration and revealed no behavioral group differences, possibly due to a ceiling effect in performance. This suggests that when behavioral performance is comparable, alterations in the attentional system in autism can still be detected at the physiological level. Importantly, this finding reduces the likelihood that differences in task difficulty account for the observed attentional alerting differences between groups.

Nevertheless, it remains important to examine whether and how TEPRs differ across groups under conditions in which autistic individuals demonstrate superior search performance. In Experiment 2, we employed the same task and stimuli under more perceptually demanding conditions and observed a search advantage in the autistic group. This pattern suggests that the pupil dilation differences observed in Experiment 1 may reflect an attentional benefit rather than generalized task difficulty. However, because Experiment 2 used masked brief displays with individually adjusted SOAs, direct comparisons of TEPRs were not feasible.

Moreover, whereas the present findings indicate reduced TEPRs in autistic adults, previous research has reported increased TEPRs in autistic toddlers. Future research should therefore determine whether these discrepancies reflect developmental changes or differences in task demands and stimulus characteristics.

6 | Conclusions

The present study reveals variations in the TEPRs between autistic and non-autistic individuals, even when task performance is comparable across groups. This variation in TEPRs may be related to alterations in the LC-NE system, as suggested by a recent study (Zhao et al. 2022). However, the present findings suggest that these variations do not necessarily reflect reduced attentional abilities and can occur even when behavioral performance shows no group differences in search speed (Experiment 1). Moreover, the finding that autistic individuals exhibited a visual search advantage under more demanding perceptual conditions—despite identical search display and task (Experiment 2)—suggests that atypical TEPRs in autism may be associated with an early-stage perceptual advantage, potentially linked to differences in the attentional alerting and orienting system.

Author Contributions

A.Y. and Z.N. conceptualized and designed the study. Z.N. conducted, collected, and analyzed the data. The original draft was written by Z.N. and A.Y.

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Ethics Statement

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments. The study was approved by the University of Haifa Institutional Review Board for Human Participants in Research (Approval No. 373/18). Written informed consent was obtained from all participants prior to participation.

Consent

All participants provided informed consent for participation and for publication of anonymized data in scientific journals.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in the Open Science Framework (OSF) repository at https://doi.org/10.17605/OSF.IO/6VYP8.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Descriptive statistics of participant characteristics by Group for Exp. 1 and Exp. 2. **Table S2:** Mean RTs and accuracy rates in each of the five conditions, in which either only one color or no color persisted from previous trial (Exp.1). **Table S3:** Mean accuracy data as a function of basic repetition and group in Experiment 1. **Table S4:** Comparison of LMEMs with pupil size as dependent variable in the basic feature priming effect. **Table S5:** Comparison of LMEMs with repetition effect. **Table S6:** Mean accuracy rates in each of the indexes of activation and inhibition in each group for Experiment 2. **Figure S1:** Activation and inhibition effect on Accuracy in Experiment 1. Accuracy as a function of target activation (A) and distractor inhibition (B) between autistic and non-autistic groups in RT. $*p < 0.05$. **Figure S2:** Group differences in TEPR as a function of (A) activation and (B) Inhibition between the autistic and non-autistic groups. The *y*-axis represents the difference in task-evoked pupillary responses (ΔTEPRs), calculated by subtracting the corresponding baseline values for activation and inhibition from their respective indices. For each index (activation and inhibition), we calculated delta pupil size by subtracting benefit (1) and cost (−1) from baseline (0). In both panels, the gray areas indicate the time intervals where significant correlations ($p < 0.01$) were observed. Shaded ribbons represent ±1 SEM. **Figure S3:** Activation and inhibition in Experiment 2. Differences in target activation (A) and distractor inhibition (B) between autistic and non-autistic groups in accuracy. $*p < 0.05$, $**p < 0.01$.