Exogenous spatial attention: Evidence for intact functioning in adults with autism spectrum disorder

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Deficits or atypicalities in attention have been reported in individuals with autism spectrum disorder (ASD), yet no consensus on the nature of these deficits has emerged. We conducted three experiments that paired a peripheral precue with a covert discrimination task, using protocols for which the effects of covert exogenous spatial attention on early vision have been well established in typically developing populations. Experiment 1 assessed changes in contrast sensitivity, using orientation discrimination of a contrast-defined grating; Experiment 2 evaluated the reduction of crowding in the visual periphery, using discrimination of a letter-like figure with flanking stimuli at variable distances; and Experiment 3 assessed improvements in visual search, using discrimination of the same letter-like figure with a variable number of distractor elements. In all three experiments, we found that exogenous attention modulated visual discriminability in a group of high-functioning adults with ASD and that it did so in the same way and to the same extent as in a matched control group. We found no evidence to support the hypothesis that deficits in exogenous spatial attention underlie the emergence of core ASD symptomatology.

Introduction

Autism spectrum disorder (ASD) is characterized by social communication deficits and restricted interests and behaviors (American Psychiatric Association, 2013). Since the earliest description of the disorder (Kanner, 1943), deficits or atypicalities in attention have been noted, and it has been proposed that attentional deficits may subserve the emergence of core ASD symptomatology (Fan, 2012; Keehn, Muller, & Townsend, 2013). An attention-based theory of ASD is

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alluring because it might be able to account for two of the primary symptoms of ASD, social and communication deficits and restricted interest and behaviors, if attentional resources are diverted to support a restricted behavioral repertoire rather than subserve the acquisition of expertise in social communication. However, attention has not been consistently defined in the ASD literature (Ames & Fletcher-Watson, 2010), and most of the empirical work done to date on ostensible attention deficits in ASD has failed to take advantage of the rigorous experimental protocols for manipulating and measuring attention that are now well established in the field of attention research.

When there is a sudden onset in the visual periphery, the processing of visual information at that spatial location is automatically facilitated. This involuntary allocation of processing resources, known as covert exogenous spatial attention, reaches its peak at ~100 ms post stimulus onset (Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989), faster than the time needed to make an eye movement or to voluntarily allocate spatial attention. Exogenous attention markedly impacts peripheral vision by increasing contrast sensitivity, enhancing spatial resolution, increasing processing speed, and modulating subjective appearance at the attended location (Cameron, Tai, & Carrasco, 2002; Carrasco, Ling, & Read, 2004; Carrasco & McElree, 2001; Herrmann, Montaser-Kouhsari, Carrasco, & Heeger, 2010; Hopfinger & Mangun, 1998; Liu, Pestilli, & Carrasco, 2005; Yeshurun & Carrasco, 1998).

Previous work on exogenous attention in ASD has produced inconsistent findings, perhaps because of methodological differences between the studies (see Discussion), and no consensus on the integrity of exogenous spatial attention in ASD has emerged. Any attentional theory of ASD must account for exogenous attention, which allows us to automatically respond to environmental demands and to react quickly to stimuli that provide behaviorally relevant information. Exogenous attention modulates both behavioral/psychophysical performance and neural activity in the visual cortex (for recent reviews, see Anton-Erxleben & Carrasco, 2013; Carrasco, 2011).

We conducted three experiments to assess the functional integrity of this system, using visual tasks for which the effects of exogenous spatial attention on early vision have been well established in typically developing populations: orientation discrimination of a contrast-defined grating (which is monotonically contingent on contrast sensitivity, e.g., Carrasco, Penpeci-Talgar, & Eckstein, 2000; Herrmann et al., 2010; Nachmias, 1967; Pestilli, Ling, & Carrasco, 2009), target discrimination with flanking stimuli at variable distances (to evaluate crowding, e.g., Yeshurun & Rashal, 2010), and target discrimination with a variable number of distractor stimuli (to assess visual search, e.g., Carrasco & McElree, 2001; Carrasco & Yeshurun, 1998). In all three experiments, we found that exogenous attention modulated visual discriminability in a group of high-functioning adults with ASD and that it did so in the same way and to a statistically indistinguishable degree as in a matched control group. The results from these three experiments provide strong evidence for intact exogenous orienting in high-functioning adults with ASD.

Materials and methods

Observers and psychophysical sessions

Fourteen high-functioning adults with ASD (19–41 years, two female) and 16 typically developing control individuals (19–47 years, three female) participated in one or more of the three exogenous attention experiments. Participants were recruited by the Center For Excellence in Autism Research (CeFAR) at the University of Pittsburgh. All participants had Full Scale and Verbal IQ scores above 79. All ASD participants had been diagnosed using *DSM-IV* criteria, and all except one met criteria for autism on both the autism diagnostic observation schedule (ADOS) and the autism diagnostic interview (ADI); one met criteria for autism on ADI but spectrum on ADOS. Experimental procedures were approved by the institutional review boards at The University of Pittsburgh and Carnegie Mellon University and by the University Committee on Activities Involving Human Subjects at NYU. Within each experiment, the participants were matched at a group level on IQ (Wechsler, 1999), gender, age, and education (Table 1). For all three experiments, there were no statistically significant group differences for Full Scale IQ, Verbal IQ, Performance IQ, or age (p values > 0.19, t tests). Participants had normal or corrected-to-normal vision, and none of the participants had been diagnosed with ADHD. Experiment 1 (contrast sensitivity, 600 trials) was completed during a single testing session, which lasted approximately 1 hr. Experiments 2 and 3 (crowding and visual search, 960 and 384 trials, respectively) were completed on a different day during a single testing session but separated by a short break. The order of the experiments was counterbalanced across participants, and the total session time was approximately 1.5 hr. Participants completed practice blocks before each experiment (Experiment 1: three blocks of 20 trials each; Experiment 2: four blocks of 24 trials each; Experiment 3: four blocks of 20 trials each). In addition, for Experiment 1, each participant

ASD group					ADOS				ADI			Control group				
Exp	Age	Verbal IQ	Full IQ	Sex	COM	SOC	COM SOC	STB	SOC	COM verbal	STB	Exp	Age	Verbal IQ	Full IQ	Sex
1	20	79	88	m	6	13	19	1	23	13	4	1	19	121	120	m
1	21	112	128	m	4	8	12	2	21	17	6	1	24	127	127	f
1	25	125	134	m	5	13	18	3	20	13	3	1	35	114	118	m
1	20	118	124	m	5	8	13	1	27	22	5	1	27	119	118	m
1	29	114	117	m	4	7	11	2	25	9	8	1	22	120	125	m
3	19	99	99	m	5	9	14	0	22	17	8	1	25	109	110	m
1–3	22	120	123	m	4	6	10	1	21	18	8	1	20	106	108	m
1–3	22	121	117	m	5	6	11	6	19	11	4	1	40	109	116	m
1–3	31	119	123	f	2	7	9	4	10	8	6	3	47	115	111	m
1–3	20	106	107	m	5	11	16	3	20	15	3	1–3	22	114	119	m
1–3	41	108	124	m	3	8	11	2	21	16	8	1–3	23	111	109	m
2, 3	21	110	107	f	7	7	14	2	27	20	6	2, 3	24	109	115	m
2, 3	23	92	84	m	4	10	14	2	23	18	7	2, 3	22	116	115	m
2, 3	41	121	129	m	6	6	12	1	32	22	10	2, 3	28	109	116	f
												2, 3	27	112	117	f
												2, 3	18	106	104	m
												2, 3	36	120	121	m

Table 1. Demographic and diagnostic information. *Notes*: ADOS, autism diagnostic observation schedule; COM, communication; SOC, social interaction; COM SOC, communication + social interaction; STB, stereotyped behaviors; ADI, autism diagnostic interview.

completed an additional block of trials to measure orientation-discrimination thresholds.

Psychophysical task

In Experiment 1, participants performed a two-alternative forced-choice orientation-discrimination task while maintaining fixation at the center of the screen (Figure 1A, B). Spatial attention was manipulated via the presentation of a peripheral precue (see below); the stimuli were sinusoidally modulated, contrast-defined grating patches (Gabors); and the target was indicated after the presentation of the gratings with a postcue. On each trial, after the presentation of the peripheral cue, four gratings were presented for 30 ms, simultaneously, in each of the four visual quadrants. Gratings were 3° of visual angle in diameter (Gaussian window $SD = 0.43°$), 2 c/°, 60% contrast, centered at 5° eccentricity in the middle of each quadrant, and with the same mean luminance as the uniform gray background. Each grating was tilted slightly with respect to vertical. The direction of tilt, clockwise or counterclockwise, was randomized on each trial independently for each of the four gratings. A response cue near fixation (0.85° green line) appeared 200 ms after the gratings disappeared and indicated which of the four gratings was the target. Targets always appeared in the lower visual quadrants, and participants were told so explicitly at the beginning of the experiment; the two upper gratings were shown so that the stimulus display would match that of another experiment not reported here. Participants indicated whether the target was tilted clockwise or counterclockwise of vertical by pressing one of two buttons. After the practice blocks, the amount of tilt was determined in pretests to equate task difficulty separately for each participant. In the pretest (200 trials, neutral cues only), a staircase procedure was used to determine the degree of tilt necessary for a performance accuracy of ~80% correct.

In Experiments 2 and 3, participants performed a four-alternative forced-choice orientation-discrimination task while maintaining fixation at the center of the screen (Figure 1C, D). Spatial attention was manipulated via the presentation of a peripheral precue (see below), and the stimuli were figures comprised of two bisecting lines. For target stimuli, the two lines bisected at the top, right, bottom, or left of an imaginary box (e.g., "T"). Distractor stimuli were made of two lines joined in the center by a third line (e.g., "H"). Targets and distractors measured 0.9° × 0.9° in size and were presented simultaneously for 100 ms at 20% contrast against a uniform gray background. The target and the distractor elements randomly and independently appeared in one of four possible orientations. Participants indicated whether the targets' two lines bisected at the top, right, bottom, or left of the center line by pressing one of four buttons. In Experiment 2—crowding—the target always appeared along the horizontal meridian at 9° eccentricity and was flanked vertically by two distractors with a center-center distance that varied randomly from trial to trial (1°, 1.5°, 2°, 2.5°, 3°, 4°, 5°, 7°, 9°, or 11°). In Experiment 3—visual search—the

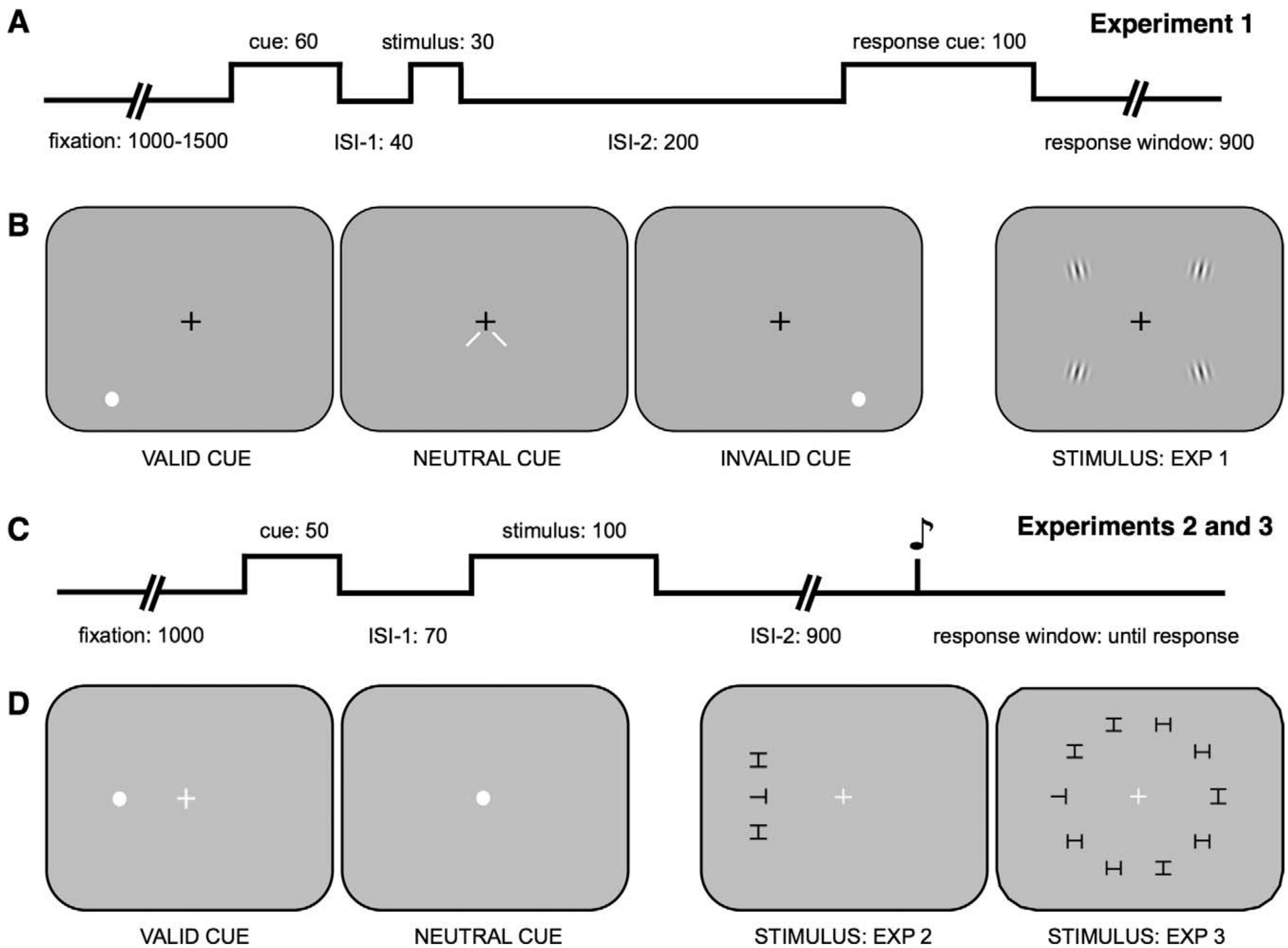

Figure 1. Experimental protocol. (A) Trial sequence, Experiment 1. ISI, interstimulus interval. Hash marks indicate extended temporal delays, not shown to scale. (B) Cue types and example stimulus, Experiment 1. (C) Trial sequence, Experiments 2 and 3. Same format as panel A. (D) Cue types and example stimuli, Experiments 2 and 3.

angular position of the target was randomly selected on each trial, and the target appeared along an imaginary 9° ring around fixation. The number of distractor elements (4, 9, 14, or 19) varied randomly from trial to trial, and all elements were equally spaced along this imaginary 9° ring, leading to a total set size of 5, 10, 15, or 20 elements.

Auditory feedback (different tones for correct and incorrect) was provided after each response in all three experiments. In Experiment 1, participants were required to respond within a 1000-ms window, and the next trial began at the end of this window. A temporal delay and a response tone were used in Experiments 2 and 3 to minimize differences in reaction times (RTs) across experimental conditions and across participants, thereby isolating the effects of attention on performance accuracy rather than on RT and preventing any speed-accuracy trade-offs that might occur differentially between the groups. After the offset of the stimulus, participants were required to wait 900 ms before responding. A tone signaled the end of this period and indicated to participants that they could respond. Participants had up to 5000 ms to make a response, and the next trial began immediately after a response was made or this upper limit was reached.

Exogenous attention manipulation

A peripheral precue (Experiment 1: 60 ms; Experiments 2 and 3: 50 ms) was used to manipulate exogenous spatial attention (Figure 1). In Experiment 1, there were three different trial types with two different precues: valid and invalid (a white dot, 0.4° in diameter, centered along the diagonal at 7.5° eccentricity) and neutral (two small white lines, 0.5°, pointing to the two lower locations from fixation). For valid trials, the precue appeared in the lower quadrant in which the target would appear, 2.5° away; for invalid trials, it appeared in the lower quadrant opposite to which the target would appear. A random third of the trials had valid cues, another third had invalid cues, and the remaining third had neutral cues. Thus, the cues were always uninformative about the upcoming target location, and participants were informed of this.

In Experiments 2 and 3, there were two trial types that utilized the same precue (a white dot, 0.4° in diameter). For valid trials, the precue appeared near the subsequent target's location at 8° eccentricity (1° closer to fixation); for neutral trials, it appeared at fixation. A random half of the trials had valid cues, and the remaining half had neutral cues. The precue was followed by a brief interstimulus interval to maximize the effects of exogenous attention (Experiment 1: 40 ms; Experiments 2 and 3: 70 ms; the stimulus-onset-asynchrony (SOA) was 100 and 120 ms, respectively). The peripheral cue in Experiments 2 and 3 was always valid and, as a result, did provide information about the spatial location of the upcoming target. It is well established in the literature, however, that ~300 ms are needed to voluntarily allocate endogenous spatial attention (e.g., Liu, Stevens, & Carrasco, 2007; Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Rolfs & Carrasco, 2012); therefore, participants would not have had time to utilize this information. Furthermore, it has also been established that cue validity does not modulate the effect of exogenous attention with the time intervals used here (Giordano, McElree, & Carrasco, 2009).

Reaction time

RT distributions for correct trials only were computed separately for each participant and separately for each experimental condition in all three experiments. The median RT for correct responses was then determined for each distribution.

Model fits

In Experiment 2, for each participant and attention condition, we modeled the effect of target-flanker distance on accuracy with the following exponential function (following Scolari, Kohnen, Barton, & Awh, 2007; Yeshurun & Rashal, 2010):

$$p_c = a\left(1 - e^{(-s(d-i))}\right) \tag{1}$$

where $p_c =$ proportion correct, $a =$ asymptote, $s =$ scaling factor, $d =$ target-flanker distance, and $i = x -$ intercept. Parameters were estimated using nonlinear least-squares fitting (MATLAB, The MathWorks, Inc., Natick, MA), using the default settings in MATLAB for the iteration number and initializing the parameter estimates with values reported by Yeshurun and Rashal (2010). The critical distance (c_d) was defined as the target-flanker distance at which performance achieved 90% of the asymptotic value and was given by the following equation:

$$c_d = i - \left(\ln(0.1)/s\right) \tag{2}$$

In Experiment 3, linear regression was use to fit straight lines to the effect of set size on accuracy. Slopes and y-intercepts were estimated separately for each participant and attention condition.

Goodness of model fits

In both Experiments 2 and 3, the coefficient of determination (R^2) was used to assess how well each model fit the data. R^2 was calculated for each of the exponential fits in Experiment 2 and each of the line fits in Experiment 3 separately for each participant and for each attention condition. Differences in R^2 values between groups were assessed using randomization tests (see below).

Visual search and crowding correlation

The deleterious effect of adding distractors in visual search (Experiment 3) could be due to crowding. Accordingly, we estimated how well the crowding data from Experiment 2 could predict performance in Experiment 3. In Experiment 3, each set size (5, 10, 15, and 20) was associated with a particular distance between the target and the nearest distractor (10.58°, 5.56°, 3.74°, and 2.82°, respectively). For each participant and attention condition, we predicted accuracy at each of these distances using the exponential fit derived in Experiment 2. The correlation between performance in visual search and estimated performance in crowding was computed across these four target-flanker distances separately for each participant and separately for each attention condition. The resulting correlation values were then Fisher-transformed, and a t test was used to determine if the correlation values were significantly greater than zero separately for each group and separately for each attention condition. An ANOVA was then used to compare the magnitude of the correlation values within attention conditions and between groups.

Eye tracking

Fixation was monitored throughout each experiment, using an infrared-video eye tracker (Eyelink, SR Research, Ottawa, Ontario; 500 Hz sampling rate). A nine-point calibration routine was completed at the start of each experimental block. Trials in which a participant's gaze deviated from fixation by more than 2° of visual angle during the presentation of the stimulus were not analyzed. Mean proportion excluded in Experiment 1, 0.11 (ASD: 0.15, control: 0.06); in Experiment 2, 0.071 (ASD: 0.10, control: 0.04); and in Experiment 3, 0.052 (ASD: 0.057, control: 0.058). For each experiment, we analyzed the proportion of fixation breaks with a two-way mixed-model ANOVA with attention condition (Experiment 1: valid, neutral, invalid; Experiment 2–3: valid, neutral) as a within-subject variable and group (ASD, control) as a between-subjects variable. There were no attention condition × group interactions in any of these experiments, providing no evidence that the distribution of fixation breaks across the attention conditions differed between groups.

Excluded participants

Some participants were excluded because of excessive fixation breaks. To assess eye movements, we computed a median-based z-score value (i.e., substituting the median for the mean in the z-score computation) for each participant's proportion of fixation breaks separately for each experiment. We excluded from all subsequent analyses any participant who had a z-score greater than two in that experiment. Two participants from the ASD group and one from the control group were excluded in Experiment 1. One ASD participant and two controls were excluded in Experiment 2. One participant from each group was excluded in Experiment 3.

In addition, three ASD participants and one control participant were excluded from Experiment 1 for being unable to perform the task above chance levels in the neutral condition. One participant was excluded from the ASD group in Experiment 2 for not reaching asymptotic performance in the neutral attention condition, resulting in a critical distance outside the tested range. Excluded participants are not included in Table 1.

Randomization tests

Because R^2 values are not normally distributed, nonparametric randomization tests were used to assess differences in model fits in Experiments 2 and 3. Participants' group labels were randomly shuffled, the mean R^2 value was recomputed for each group, and the difference was recorded. This procedure was repeated 1,000 times to obtain a null distribution of between-group differences in R^2 values. The p value reported is the proportion of null distribution values greater than or equal to the actual difference in R^2 value; absolute values were used in the computation to make this a two-tailed test.

Ruling out possible stimulus confounds

We tested for response biases that might have contributed to any differences in performance across the group, thereby possibly confounding the interpretation of the results. Specifically, in Experiment 1, ASD participants might have exhibited a bias to respond "counterclockwise" when the target appeared on the left side. In Experiment 2, ASD participants might have exhibited a bias to report that the lines bisected on the right when the target appeared on the right. To ensure that there were no such visual-field, stimulus-response congruency effects that might have impacted our results in Experiment 1, we computed a three-way, mixed-model ANOVA with target side (left, right) and target tilt (clockwise, counterclockwise) as within-subject variables and group (ASD, control) as a between-subjects variable. An analogous ANOVA was computed for Experiment 2 with target-arm eccentricity (T junction in the outer, inner position) replacing target tilt. For both experiments, and for both accuracy and reaction time (RT), we found no main effect of side, no main effect of tilt/eccentricity, no side × group or tilt/eccentricity × group interactions, and no side × tilt/eccentricity × group interactions. In short, there were no possible stimulus confounds.

Results

Experiment 1: Effects of attention on contrast sensitivity

We found that exogenous attention modulated contrast sensitivity during an orientation-discrimination task in the same way and to a statistically indistinguishable degree in both groups (Figure 2). Accuracy, RT, and inverse efficiency measures (RT divided by accuracy, e.g., Kimchi & Peterson, 2008) were each analyzed with a two-way mixed-model ANOVA with cue (valid, neutral, invalid) as a within-subjects variable and group (ASD, control) as a between-subjects variable (Table 2). There was a main effect of cue for accuracy (Figure 2A), RT (Figure 2C), and inverse efficiency. Accuracy was higher, RT was faster, and performance was more efficient for the valid than the neutral cue (two-tailed, paired t tests, $ps < 0.05$), which, in turn, was higher, faster, and more efficient than for the invalid cue (two-tailed, paired t tests, $ps < 0.005$). There was no main effect of group

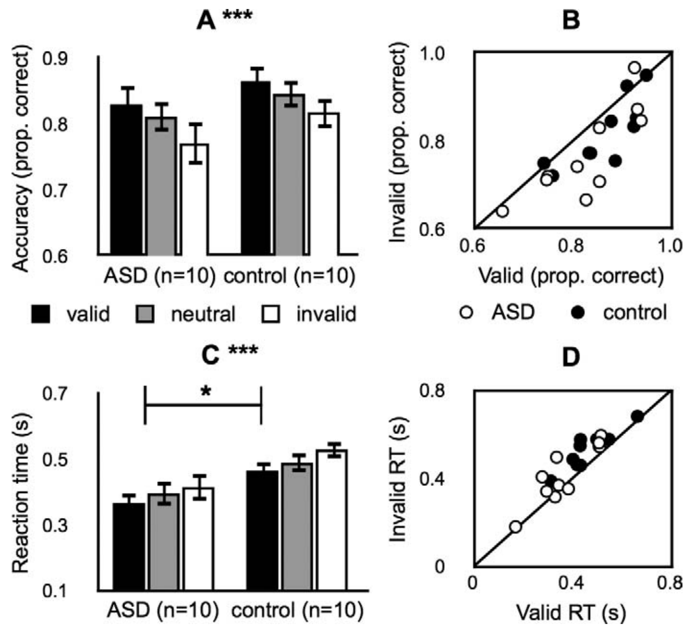

Figure 2. Experiment 1: contrast sensitivity. (A) Accuracy in the orientation-discrimination task. Black bars, valid trials. Gray bars, neutral trials. White bars, invalid trials. ***, significant main effect of attention ($p < 0.001$). Error bars, standard error of the mean across participants. (B) Individual accuracy data. x-axis, valid trials. y-axis, invalid trials. White circles, ASD group. Black circles, control group. Black line, unity line. (C) Reaction time. Same format as panel A. *, significant main effect of group ($p < 0.05$). Same format as panel A. (D) Individual reaction times. Same format as panel B.

for accuracy or efficiency, indicating that overall proportion correct and overall efficiency did not differ between the groups. There was, however, a main effect of group in RT with the ASD group exhibiting significantly faster RTs across all attention conditions. There were no cue × group interactions for accuracy, RT, or efficiency. This means that the magnitudes of the cueing effects were indistinguishable between the groups, providing evidence that peripheral cues modulated accuracy, RT, and efficiency in the same way and to a statistically indistinguishable degree in ASD as in typical development. The pattern of results was consistent across participants (Figure 2B, D).

Potential group differences in task difficulty and/or missed responses did not confound these results. Orientation-discrimination thresholds were determined in pretests to equate task difficulty separately for each participant. The amount of tilt (angular degrees from vertical) at which participants performed the task was indistinguishable between the groups (ASD: mean = 23°; range = 2.5°–40°; control: mean = 17°; range = 2.2°–37°; *t* test, $p = 0.31$), ruling out the possibility that unequal task difficulty might have masked real differences in task performance. Additionally, participants were instructed to be as accurate as possible but to still respond within the 1000 ms response window. Missed responses were treated as incorrect, but the proportions of missed responses were low and statistically indistinguishable across groups (ASD: 0.027, control: 0.028; *t* test, $p = 0.96$). Repeating the ANOVAs with these trials excluded, rather than counted as incorrect responses, did not qualitatively change the outcome, and the results supported the same conclusions.

Experiment 2: Effects of attention on crowding

In Experiment 2, we found that exogenous attention modulated the critical distance during a visual crowding task in the same way and to a statistically indistinguishable degree in both groups (Figure 3). We fit exponential functions to model the effect of target-flanker distance on accuracy. Critical distance values (i.e., the target-flanker distance at which accuracy reached 90% of the asymptotic value, see Materials and methods) were subjected to a two-way mixed-model ANOVA with cue (valid, neutral) as a within-subjects

	Cue	Group	Cue × group interaction
Exp 1: accuracy	*$F(2, 18) = 13.16$, $p < 0.001$*	$F(1, 18) = 1.30$, $p = 0.27$	$F(2, 36) = 0.23$, $p = 0.79$
Exp 1: reaction time	*$F(2, 18) = 19.10$, $p < 0.001$*	*$F(1, 18) = 4.77$, $p < 0.05$*	$F(2, 36) = 0.72$, $p = 0.50$
Exp 1: efficiency	*$F(2, 18) = 21.59$, $p < 0.001$*	$F(1, 18) = 2.91$, $p = 0.11$	$F(2, 36) = 0.56$, $p = 0.58$
Exp 2: critical distance	*$F(1, 14) = 18.01$, $p < 0.001$*	$F(1, 14) = 0.01$, $p = 0.93$	$F(1, 14) = 0.99$, $p = 0.34$
Exp 2: reaction time	$F(1, 14) = 1.71$, $p = 0.21$	$F(1, 14) = 0.95$, $p = 0.35$	$F(1, 14) = 1.81$, $p = 0.20$
Exp 3: y-intercept	*$F(1, 16) = 25.17$, $p < 0.001$*	$F(1, 16) = 0.01$, $p = 0.93$	$F(1, 16) = 0.31$, $p = 0.58$
Exp 3: slope	*$F(1, 16) = 13.66$, $p < 0.005$*	$F(1, 16) = 1.94$, $p = 0.18$	$F(1, 16) = 0.26$, $p = 0.61$
Exp 3: reaction time	*$F(1, 16) = 15.76$, $p < 0.005$*	$F(1, 16) = 1.46$, $p = 0.24$	$F(1, 16) = 1.03$, $p = 0.39$
Visual search and crowding correlation	$F(1, 16) = 0.001$, $p = 0.98$	$F(1, 16) = 1.26$, $p = 0.73$	$F(1, 16) = 0.60$, $p = 0.45$

Table 2. Experiments 1, 2, and 3 statistics. *Notes*: *F* statistics and *p* values for two-way mixed-model ANOVAs with cue (Experiment 1: valid, neutral, invalid; Experiments 2 and 3: valid, neutral) as a within-subjects factor and group (ASD, control) as a between-subjects factor. Italics, statistically significant differences.

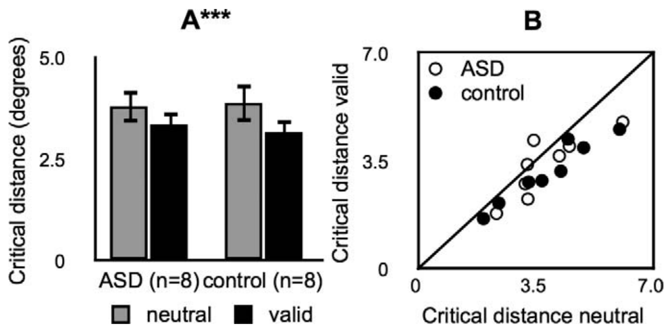

Figure 3. Experiment 2: crowding. (A) Target-flanker critical distance. Black bars, valid trials. Gray bars, neutral trials. ***, significant main effect of attention ($p < 0.001$). Error bars, standard error of the mean across participants. (B) Individual critical distances. x-axis, neutral trials. y-axis, valid trials. White circles, ASD group. Black circles, control group. Black line, unity line.

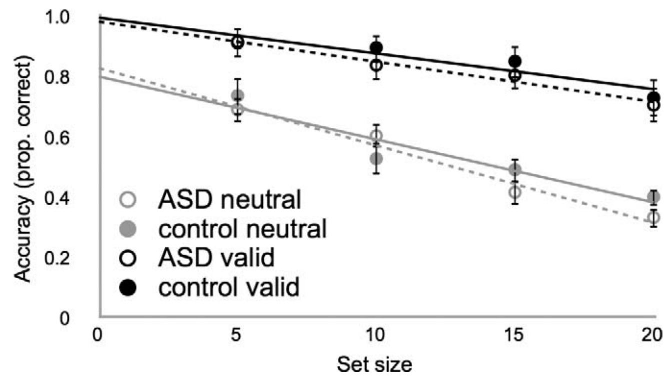

Figure 4. Experiment 3: visual search. Accuracy in visual search as a function of set size. Open circles and dashed lines, ASD group. Closed circles and solid lines, control group. Black, valid trials. Gray, neutral trials. Error bars, standard error of the mean across participants.

variable and group (ASD, control) as a between-subjects variable (Table 2). There was a main effect of cue, indicating a significant reduction in the critical distance in valid attention trials compared with neutral trials (Figure 3A). There was no main effect of group, meaning that crowding occurred in "integration windows" that were indistinguishable in size between groups (Pelli & Tillman, 2008). Finally, there was no cue × group interaction, indicating that valid peripheral cues reduced the critical distance in both groups and that this change in critical distance was statistically indistinguishable between groups. The pattern of results was consistent across participants (Figure 3B).

Potential group differences in model-fit quality or estimated parameters did not obscure true differences between groups. Two-way mixed-model ANOVAs were conducted on each of the exponential model parameters separately (x-intercept, scaling factor, and asymptote), and there were no significant group differences or significant cue × group interactions resulting from any of these analyses. The exponential function fit the data well, and the goodness of fit was not significantly different between the groups (mean R^2 values: ASD = 0.924; control = 0.919; randomization test, $p = 0.81$).

There was no evidence for differences in RT between groups. Median RTs (correct trials only) were subjected to a three-way mixed-model ANOVA with cue (valid, neutral) and target-flanker distance as within-subjects variables and group as a between-subjects variable. There were no significant interactions between any of these factors and no main effect of group. After collapsing across target-flanker distances and cue conditions, there was still no evidence of a difference in RT between the groups (t test, $p = 0.35$).

Experiment 3: Effects of attention on visual search

In Experiment 3, we found that exogenous attention modulated target discriminability during a visual search task in the same way and to a statistically indistinguishable degree in both groups (Figures 4 and 5). We fit straight lines to accuracy as a function of set size and then submitted slope and y-intercept values to two-way mixed-model ANOVAs with cue (valid, neutral) as a within-subjects variable and group (ASD, control) as a between-subjects variable (statistics in Table 2). There was a main effect of cue on both parameters (Figures 4, 5A, C), indicating that exogenous attention significantly decreased the impact of additional distractor elements (flattened slope) and improved overall performance (y-intercept). There was no main effect of group, meaning that both the impact of additional distractor elements (slope) and the overall performance (y-intercept) were indistinguishable between the groups. There was no cue × group interaction for either analysis, meaning that the effects of cueing on slope and y-intercept were statistically indistinguishable between groups. The pattern of results was consistent across participants (Figure 5B, D).

Potential group differences in fit quality and/or RTs did not confound these results. Straight lines fit the data well, and the goodness of fit was not significantly different between the groups (mean R^2 values: ASD = 0.81; control = 0.71; randomization test, $p = 0.253$). Median RTs (correct trials only) were subjected to a three-way mixed-model ANOVA with cue and set size as within-subjects variables and group as a between-subjects variable. There were no significant interactions between any of these factors and no main effect of group. Further, there was no evidence of a difference in

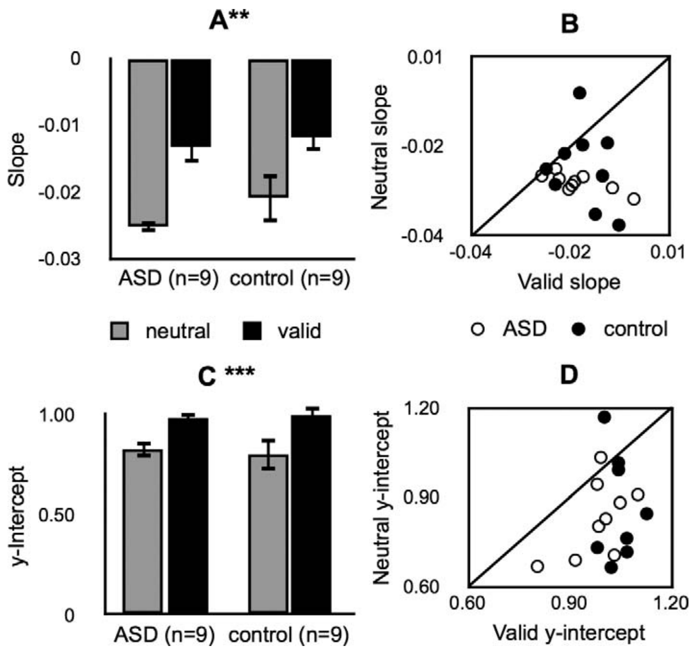

Figure 5. Experiment 3: visual search. (A) Slope of the regression line. Black bars, valid trials. Gray bars, neutral trials. **, significant main effect of attention ($p < 0.005$). Error bars, standard error of the mean across participants. (B) Individual slopes. White circles, ASD group. Black circles, control group. Black line, unity line. (C) Y-intercept of the regression line. Same format as panel A. ***, significant main effect of attention ($p < 0.001$). (D) Individual y-intercepts. Same format as panel B.

RT between the groups after collapsing across cue and set size conditions (t test, $p = 0.24$).

For the 16 participants (eight from each group) who completed both Experiments 2 and 3, performance in visual search significantly correlated with estimated performance in crowding to a statistically indistinguishable degree in both groups and in both valid and neutral trials. Distance to the nearest distractor element was determined for each of the set sizes in the visual search experiment, and estimated crowding accuracy was computed using the exponential fit derived in the crowding experiment separately for each participant and separately for each attention condition. With target-flanker distances equated across experiments, performance at each set size in visual search was positively correlated with estimated performance in crowding in both groups and in both attention conditions (mean correlation values: ASD neutral, 0.88; ASD valid, 0.72; control neutral, 0.79; control valid, 0.88; t tests, p-values < 0.005). A two-way mixed-model ANOVA with cue (valid, neutral) as a within-subjects variable and group (ASD, control) as a between-subjects variable revealed no significant interactions and no significant main effects (Table 2). This indicates that the degree of correlation between visual search performance and estimated performance in the crowding task did not differ between groups or between attention conditions. Taken together, this is evidence that not only are the effects of crowding consistent between experiments, but also, and importantly for this study, that the ability of exogenous spatial attention to alleviate crowding operates in a statistically indistinguishable manner for both groups in both tasks.

ASD severity and attention effects

ASD symptom severity did not significantly correlate with the magnitudes of the attention effects. For each experiment and for each attention effect reported (i.e., changes in accuracy and RT, Experiment 1; changes in critical distance and RT, Experiment 2; changes in slope, intercept, and RT, Experiment 3), we computed the correlation between the magnitudes of the attention effects and ADOS scores across participants in the ASD group separately for each attention effect and separately for each of the three ADOS subscores. Before multiple comparison correction, the change in RT (valid minus invalid) in Experiment 1 correlated with stereotyped behavior scores on the ADOS ($p = 0.02$). But given that we performed 21 tests, the critical p with a Bonferroni correction would be $p < 0.0024$, and the correlation in question does not survive this correction. Furthermore, we note that the same ΔRT versus stereotyped behavior correlation yielded a nonsignificant correlation in the other direction in Experiment 3. In sum, there is no evidence for a correlation between the magnitude of the attention effect and symptom severity.

Discussion

In three different tasks, we found that exogenous spatial attention cues evoked robust enhancements in performance for adults with ASD, statistically indistinguishable from the performance enhancements observed in a matched control group. In Experiment 1, attention modulated performance accuracy and RTs when participants judged the orientation of a grating. In Experiment 2, attention alleviated crowding in the visual periphery by decreasing the target-flanker distance needed to discriminate the orientation of a letter-like figure. In Experiment 3, attention modulated performance in visual search by increasing performance overall and reducing the effect of added distractors. The magnitudes of these cueing effects were statistically indistinguishable from a matched control group in all three experiments. Taken together, these data provide strong evidence for intact exogenous attention function in high-functioning adults with ASD.

The spatial attention literature in ASD is full of inconsistent findings (for reviews, see Ames & Fletcher-Watson, 2010; Fan, 2012; Keehn et al., 2013; Simmons et al., 2009). Despite this large body of empirical work, only a handful of previous studies have assessed exogenous spatial attention function in ASD by pairing a peripheral precue with a covert discrimination task (Haist, Adamo, Westerfield, Courchesne, & Townsend, 2005; Iarocci & Burack, 2004; Renner, Grofer, Klinger, & Klinger, 2006; Robertson, Kravitz, Freyberg, Baron-Cohen, & Baker, 2013; Townsend, Harris, & Courchesne, 1996, task 2). Inconsistent with our results, ASD-associated deficits in exogenous attention were reported in all but one (Iarocci & Burack, 2004) of these previous studies. However, serious methodological concerns limit the validity and interpretability of these studies.

Research on speed-accuracy trade-offs and attention have shown that to interpret accuracy-based cueing effects, it is necessary to analyze RT to rule out possible trade-offs (Carrasco, Giordano, & McElree, 2004, 2006; Carrasco & McElree, 2001; Giordano et al., 2009). Two of the previous studies reporting deficits in exogenous attention in ASD (Renner et al., 2006; Townsend et al., 1996, task 2) did not report RT analyses or results. In the most straightforward example of a speed-accuracy trade-off, the ASD group might have sped up on valid trials compared to invalid trials, which would have lowered accuracy in valid but not invalid trials, thus resulting in a decrease in the magnitude of the cueing effect (i.e., performance in valid minus performance in invalid trials). This smaller cueing effect could be accounted for by the change in RT rather than a difference in attention between the groups. In a similar way, control participants could have slowed down on valid trials compared to invalid trials, thus artificially inflating the magnitude of their accuracy-based attention effect. Without comparing the RT cueing effects between groups, it is impossible to make a fair comparison of the accuracy-based cuing effects.

A previous fMRI study reported weaker modulation of performance accuracy with cue validity in the ASD group with no group differences or group $\times$ attention interactions in RT (Haist et al., 2005). However, eye movements were not explicitly monitored during the task. Instead, the authors inferred eye movements from the fMRI responses in regions of interest placed over the eyes of the participants. The inferred eye movements differed between groups, and differences in eye position during the presentation of the precues, the target, or both could drastically impact the behavioral effects reported.

The last relevant study reported a sharper gradient of spatial attention in adults with ASD compared to controls (Robertson et al., 2013). The authors used a 100% valid precue along the horizontal meridian and placed the target at one of three distances (near, mid, and far) above or below the location of the precue. They found that the change in inverse efficiency scores (a combined metric of accuracy and RT) from near to far distances was more drastic for the ASD group than for the control group. Unfortunately, without a neutral or invalid cue condition against which to compare the valid condition, it is impossible to rule out alternative interpretations. For example, a neutral condition may have revealed a similar gradient of performance in the ASD group, and when the change in performance was computed (i.e., valid versus neutral), it would have been identical between groups. To conclude anything about attention, performance in the same task at the same location must be compared for two or more different cueing conditions (valid, invalid, neutral) (e.g., Carrasco, 2011). Furthermore, the Robertson et al. study confounded exogenous and endogenous attention. Their experiments were performed with three SOAs between the cue and target. The main result, an ostensible "attention gradient effect," was evident only for the medium and long SOAs and absent for the shortest SOA. In their long-SOA condition, participants had enough time to allocate endogenous attention to the target location while the stimulus was still present (e.g., Grubb et al., 2013). Indeed, given that the cues were always valid (100% predictive of target location), this would have been the optimal strategy. The different SOAs, therefore, most likely corresponded to exogenous attention for the shortest SOA, endogenous attention for the longest SOA, and a mixture of the two for the medium SOA. Taken together, is impossible to know if the steeper drop in performance with cue-target distance in the ASD group was due to a combination of endogenous and exogenous attention or to some other nonattention-related factor.

We can rule out confounding effects of RT in our study. In Experiment 1, we measured performance accuracies and RTs. Despite faster overall RTs in the ASD group (see below), we showed equivalent attentional modulation of both accuracy and RTs in the predicted direction in both groups, ruling out any speed-accuracy trade-offs specific to a particular attention condition. Further, these results remained when a combined measure of accuracy and RT was used (i.e., inverse efficiency). In Experiments 2 and 3, we introduced a response-delay period (1000 ms) to minimize differences in RT across participants, and we found no group differences for RT and no group $\times$ attention interactions in either of these experiments.

Significantly faster overall RTs for the ASD group in Experiment 1 should not be interpreted as an attention-related difference. It simply means that the ASD group was responding more quickly than the control group in all three attention conditions. The magnitudes of the changes in RT due to attention (i.e., the RT cueing effects) were statistically indistinguishable between groups (interaction p value: 0.50). Ours is not the first study to show faster overall motor responses in studies of attention in ASD. Chawarska, Klin, and Volkmar (2003) found equivalent between-group attention effects for congruent versus incongruent eye gaze cues but faster overall saccadic latencies for the ASD group.

We found robust effects of crowding in both groups (Experiment 2), adding to a growing body of inconsistent findings on crowding in ASD. A study in children with ASD found no group differences in visual search but did find that adding flankers in a covert orientation-discrimination task affected the control group more than the ASD group (Baldassi et al., 2009). Using centrally presented Landolt-C optotypes, a second study found no group differences in visual acuity but did observe that the addition of flankers led to greater foveal crowding in the control group relative to the ASD group (Keita, Mottron, & Bertone, 2010; but see Levi, 2008 for the current debate on whether or not genuine crowding occurs in the fovea). Such evidence for reduced crowding in ASD is in conflict with our conclusions, but the difference in findings might be due to differences in methodology. Neither of these studies systematically manipulated target-flanker distances in the periphery; the former used eight flankers at a fixed target-flanker distance in the periphery, and the latter used multiple flanking distances but for centrally presented (i.e., foveal) targets. Consistent with our results, a third study used a QUEST procedure (Watson & Pelli, 1983) to evaluate critical spacing for target discrimination in the periphery and found no evidence for differences in crowding between the ASD group and the control group (Constable, Solomon, Gaigg, & Bowler, 2010). We extend these results to show that exogenous attention alleviates crowding and that it does so in both groups in an indistinguishable manner. That attention reduces the critical distance in typically developing populations has been shown previously across a number of eccentricities (Yeshurun & Rashal, 2010).

We found no evidence for differences between the groups in visual search (Experiment 3), ostensibly inconsistent with the extant literature on visual search superiority in ASD. Compared to matched controls, children and adults with ASD have been found to be faster at target detection and less affected by set size in difficult feature and conjunction search tasks (e.g., O'Riordan, 2004; O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001). In these studies, participants were allowed to move their eyes, and evidence for superior performance has been confined to measures of RT. Consistent with our results, studies that have probed search superiority using covert, accuracy-based protocols have found performance to be indistinguishable between groups (Baldassi et al., 2009). We speculate, however, that given the faster RTs observed in Experiment 1 for the ASD group, faster overall performance in Experiment 3 (i.e., independent of attention) might have been observed had we used an RT-based approach. It is an open empirical question as to why superior performance should manifest in RT during overt search but not in accuracy during covert search. We believe this to be a worthwhile topic for future research.

Small sample size should not limit the generalizability of these findings. Each experiment used a psychophysical protocol in which approximately five participants is typical, yielding large attention effects that were consistent across individuals and experiments (Figures 2 through 5). The ANOVAs of the accuracy data revealed that group $\times$ attention interaction F values were all less than one (indicating that the within-group variability was larger than the between-group variability; Table 2). Each experiment was statistically independent, and they all showed the same pattern of results: large attention effects that were statistically indistinguishable between groups. Furthermore, the RT results from Experiment 1 indicate that we did have adequate statistical power to detect a between-group difference. Lastly, for three experiments, the magnitude of individual attention effects in the ASD group were not significantly correlated with ASD severity as indexed by ADOS scores. Given such robust attention effects and no evidence for heterogeneous performance across the participants in each group, we take this as strong evidence against the notion that deficits in exogenous attention underlie the core ASD-associated deficits present in high-functioning adults with ASD.

Despite strong assertions that attention is disrupted in ASD (Fan, 2012; Keehn et al., 2013; Townsend & Westerfield, 2010), this is still a contentious and hotly debated issue (Ames & Fletcher-Watson, 2010; Simmons et al., 2009). Our strategy has been to take a rigorous psychophysics-based approach, using protocols and experimental manipulations that are well understood in typically developing populations. In a previous study, we provided evidence for intact control of voluntary spatial attention in ASD under a variety of task demands (e.g., manipulation of timing and spatial spread of attention; Grubb et al., 2013). Here, we have taken a similar approach to the study of exogenous spatial attention, which plays a critical role in modulating early vision, and provide evidence that it operates reflexively and automatically in high-functioning adults with ASD, just as in typically developing populations. Taken together, both studies provide evidence that high-functioning adults with ASD do not have deficits in covert attention. The functional integrity of endogenous and exogenous attention in

these individuals raises significant doubts about the proposal that covert attentional deficits subserve core ASD symptomatology.

Keywords: covert attention, exogenous attention, crowding, visual search, contrast sensitivity, adults, autism, ASD

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