Effects of Autistic Trait-Related Joint Attention on Visual Working Memory

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Abstract

Background: Social attention deficits have been found in individuals with high autistic traits in the non-clinical population However, the eye movement patterns triggered by gaze direction still need to be explored in individuals with different levels of autistic traits, and it remains unknown whether autistic traits can modulate the relationship between joint attention and visual working memory. The aims of this study were to investigate the effect of autistic traits on joint attention and whether autistic traits could further influence visual working memory performance through joint attention.

Methods: A total of 46 participants who scored in the top and bottom 20% on the Chinese version of the Autism-Spectrum Quotient (AQ) were divided into high- and low-AQ groups. We used a combination of the cueing paradigm, change detection task, and eye-tracking technique to explore behavioral performance and eye movement patterns. The 50% validity gaze and dot cues were set as social and nonsocial cues, respectively.

Results: The low-AQ group showed shorter reaction times for the gaze-cued location but not for the dot condition and not for the high-AQ group. The low-AQ group had a higher fixation proportion, more fixation counts both in the gaze-cued and dot-cued locations, and shorter entry time into the target ROI under the valid gaze condition. The high-AQ group only showed a dot cueing effect with a higher fixation proportion and more fixation counts in dot-cued location.

Limitations: The small number of memory items may have led participants to encode polygons into long-term memory, which limits the only interpretation of results on visual working memory. In addition, participants in this study were all undergraduates or graduate students, which may limit the generalizability of our findings to a broader population.

Conclusions: This finding suggest that autistic traits influence the pattern of attention triggered by gaze and dot cues. Individuals with low-AQ were more adept at using gaze cues to direct attention, while high-AQ individuals were less sensitive to gaze cues and preferred non-social cues. The difference in joint attention further affected the speed of visual working memory.

Background

Joint Attention (JA) is when two individuals pay attention to the same object so as to share their interest and perceptual experience regarding a particular object [1]. It includes voluntary joint attention (VJA) and reflexive joint attention (RJA). VJA refers to an individual's ability to actively draw others' attention to something of interest to them, such as using posture and eye contact to guide others' attention to the object and themselves. RJA refers to an individual's ability to follow social cues, such as gaze or gestures, to shift their visual attention, including gaze-following and gesture following [2]. At each stage of individual development, RJA is elicited by social cues, such as gaze, face orientation, head orientation, and body posture [3, 4], playing a crucial role in social development. Numerous researchers have found that the phenomenon of gaze-following emerges as early as infancy and that social cues produce

stronger cueing effects than symbols such as arrows without social meaning [5, 6], even without requiring conscious engagement [7]. However, in many studies, individuals with autism spectrum disorder (ASD) have shown deficits in JA, especially in gaze-related studies, where ASD individuals showed less frequent gaze-following [8]. When presented with both eye and head cues, they relied more on head cues for gaze-following than on eye cues [9]. In comparative studies of gaze and arrows, some studies have found deficits in gaze-elicited attentional orientation in people with ASD compared to that in normal individuals, suggesting that ASD individuals are insensitive to gaze [10, 11].

However, some researchers have found inconsistent results in individuals with ASD. A study of two-year-old children with autism, using saccadic reaction time as an indicator, showed that both children with autism and typically developing children exhibited an attentional bias toward the gaze cued targets of 50% validity [12]. To further investigate whether the above performance in children with autism was due to the non-biological motion of the eye, another experiment employed squares as non-biological motion cues and found that neither group showed attentional bias toward the cued targets. In a change blindness paradigm, both ASD adults and normal participants perceived change more quickly and accurately in the gaze-change condition than in the square-change condition [13]. Similar results were also found in saccadic reaction time (RT) and proportions of gaze following under 50% valid gaze cues by Kuhn et al. [14]. Other studies found that although there was no difference between ASD individuals and normal participants in gaze-following behaviors, individuals with ASD had significantly shorter fixation durations for cued objects than normal participants [15, 16]. In response to these inconsistent results, it has been suggested that although ASD individuals respond normally to gaze-following, the subsequent abnormalities in fixation duration for targets may indicate that they use gaze as a directional signal rather than as a reference cue, thus ignoring the social significance represented by gaze cues [14, 17]. In other words, patients with ASD process gaze cues in the same way they process non-social cues [18]. However, some of these studies did not use non-biological motion cues for comparison [14, 15, 17]. In contrast, other studies that used non-biological cues for comparison, such as squares [12] and arrows [16], did not induce a sufficiently strong sense of motion to effectively rule out the influence of cue dynamics on the experimental results. Therefore, further research is still required on whether patients with ASD only use gaze cues as non-biological motion cues and whether their deficits in social cognition are related to this abnormality.

Due to the difficulties in conducting studies on individuals with ASD, many researchers have recently begun to focus on non-clinical groups of individuals with high levels of autistic traits. The Autism-Spectrum Quotient (AQ) has been widely used as a self-assessment scale to measure the level of autistic traits in individuals [19]. On the continuum of autistic traits, individuals with autism who score highly on the AQ are at the top of the continuum. In contrast, individuals with non-clinical but relatively high levels of autistic traits have performed similarly to individuals with ASD in genetic and other experimental studies [20]. Several behavioral studies have found that individuals with high levels of autistic traits have abnormal responses to gaze. For example, the normal parents of individuals with ASD did not show the same cueing effects as the control group at 50% gaze cues [21]. In a cross-modal study with gaze and auditory targets, it was found that the RT of both high and low autistic trait groups showed cueing effects

under the shorter stimulus onset asynchrony (SOA, 200 ms) condition. However, the cueing effects disappeared under the longer SOA (800 ms) condition in the high autistic trait group, indicating that gaze-triggered JA under cross-modal conditions is transient in individuals with high autistic traits [22]. Eye-tracking studies found that during real-time interactions with the experimenter, the high autistic trait group showed shorter fixation duration on the experimenter's eyes compared to the low autistic trait group [23] as well as shorter and less frequent saccades, and reduced visual exploration [24]. Most current studies have found that autistic traits can affect individuals' attentional responses to gaze, but the mechanisms and effects of JA still require further investigation using eye-tracking technology. Therefore, by using gaze and dot cues with enhanced properties of non-biological motion, this study focused on the effects of autistic traits on JA and the differences in performance between the high-AQ group and low-AQ group on gaze and non-biological motion cues.

JA is important for verbal comprehension and object learning. Individuals use gaze cues to engage in more complex cognitive behaviors, even when cue validity is 50%. Social motivation theory suggests that individuals with ASD show deficits in the processing of social stimuli, which reduces the reward value of social stimuli. These processing deficits will reduce the social orientation of individuals with ASD, decrease their willingness and preference for social maintenance and social interaction, and ultimately give rise to abnormalities in their overall social functioning. In other words, the decrease in the intrinsic interest of patients with ASD in social stimuli will lead to deficits in their social cognition [25]. A word learning study found that normal controls used gaze cues and performed better on cued words, while individuals with ASD were unable to or less likely to use gaze cues to learn words [26]. Eye movement results from a similar study found that normal controls fixated longer on cued target objects, but patients with ASD showed poorer word learning performance due to less gaze-following of cued targets and shorter fixation duration [27]. These results suggest that JA deficits in patients with ASD can further affect their higher cognitive processing. In our interactions with the outside world, we share information about others' attention through JA. This is a process that not only involves attention, but also requires the involvement of working memory, which helps us keep track of others' intentions, remember important information, and prepare for future needs [28]. Effective JA enhances an individual's performance in visual working memory. Researchers have argued that during the encoding phase (pre-cue), individuals encode more of the memory objects at the cued location, which modulates the processing of objects that enter the working memory [28], whereas during the maintenance phase (retro-cue), individuals prioritize the maintenance processing of memory items at the cued location, which modulates the processing of objects already stored in working memory. Therefore, cued objects have been found to elicit better memory performance [29]. Most studies use pre-cues to investigate the effects of JA on visual working memory during the encoding phase. However, it remains unclear whether, during the working memory maintenance phase, individual differences (e.g., the level of autistic traits) modulate the processing of objects already stored in working memory through JA. Thus, the second question of interest in the present study is whether the JA ability of individuals with different autistic trait levels will affect the maintenance of memory items, which has important implications for understanding the diversity of social cognitive development in the normal population.

Therefore, in the current study, we focused on individuals with different levels of autistic traits and used a combination of behavioral responses and eye-tracking techniques to investigate the following two questions at greater depth. First, we examined how autistic traits affect the JA behaviors of individuals and how this effect differs from that of non-social cues. Second, we examined whether the JA characteristics of individuals with high autistic traits may further affect the maintenance of visual working memory. With reference to the experimental paradigm by Nie et al. [30], which combines cueing and change detection, two types of cues were introduced in this study, with social cues set as the eye region of the face and non-social cues as dots. Cue validity was set at 50%. The present study hypothesized that compared to individuals with low autistic traits, individuals with high autistic traits would show insensitivity to social cues, deficits in JA, and less gaze-following, which would have consequent effects on their visual working memory performance, thus resulting in lower response accuracy and longer RTs to probes at the gaze-cued location.

Methods

Participants

A total of 220 AQ questionnaires were randomly distributed among undergraduates and graduate students, and 207 valid questionnaires were finally returned. Before the experiment, the required sample size was calculated using G*power software with an effect size f value of 0.25, α value of 0.05, and a power value of 0.95. This indicated that the required sample size was 36 people. The high- and low-AQ groups were divided according to previous grouping criteria [31, 32] and the range of AQ scores for the two groups [33, 34]. According to their total scores, those who scored in the top 20% and bottom 20% were selected. The high-AQ group in this study had an AQ score of ≥ 124, and the low-AQ group had an AQ score of ≤ 108. Based on the participants' willingness to participate in the experiment, 47 participants were recruited initially, but one failed to pass the eye movement calibration. Eventually, 46 participants were divided into two groups. The high-AQ group included 23 participants (5 males and 18 females), with a mean age of 19.70 ± 1.64 years, an AQ score range of 124−137, and a mean score of 128.95 ± 3.89. The low-AQ group included 23 participants (9 males and 14 females), with a mean age of 20.39 ± 2.46 years, an AQ score range of 91−108, and a mean score of 103.09 ± 4.70. An independent sample t-test was performed on the AQ scores of the high and low groups, and there was a significant difference between the AQ scores of the two groups ($t(1, 44) = 25.87$, $p < 0.001$, Cohen's d $= 7.63$, 95% CI = [23.31, 28.43]). There was no significant difference in gender composition between the two groups ($\chi^2 = 1.64$, $df = 1$, $p = 0.20$). All participants had normal or corrected visual acuity and normal auditory acuity, were right-handed, and had no history of psychiatric disorders. All participants volunteered to participate in this experiment and were compensated after completing the experiment. Informed consent was obtained according to procedures approved by the Anhui Normal University ethics committee.

Experimental materials and instruments

AQ questionnaire

The AQ questionnaire, developed by Baron-Cohen in 2001, had primarily been used to measure autistic traits in non-clinical populations. Studies have shown that people with clinically diagnosed autism have higher AQ scores [19, 35, 36]. Zhang et al. [36] translated and revised the Chinese version. The questionnaire includes five dimensions: social skills, attention shifting, attention to detail, communication, and imagination, with 50 items in total. Each item has four options: "definitely agree," "slightly agree," "slightly disagree", and "definitely disagree," which are scored using a 4-point Likert scale. Higher scores indicate higher levels of autistic traits. The internal consistency coefficient of the revised Chinese version was 0.81, the test-retest reliability was 0.89, and the internal consistency coefficients of the subscales were between 0.62 and 0.76. In this study, the internal consistency coefficient of AQ was 0.70.

Materials and apparatus

With reference to the experiment by Nie et al. [30], gaze cues were used as social cues in this study, wherein six images of real faces taken by a digital camera were processed by FaceGen Modeler version 3.4 to form faces that gazed left, right, or straight ahead. Then, the images were processed using Photoshop CS4 to retain only the eye region. The non-social dot cue consisted of a black line segment with two black dots on it. The line segment length was consistent with the width of the presented gaze, and the dot size and position remained consistent with the pupil of the gaze cue. The memory and probe items were selected from six irregular polygons (subtending 1.5°× 1.5° each) [37]. Two irregular polygons were randomly presented on the memory interface at a time, located to the left and right of the screen, both 3.5° from the center. The probe could not be the same as the mirror image of the memory items.

A program written using E-prime version 2.0 was used to present the stimuli, control the experimental process, and collect the behavioral response data. The stimuli were presented on a 19-inch monitor (resolution: 1024 × 768, refresh rate: 75 Hz). The Hi-Speed eye tracker manufactured by SensoMotoric Instrument (Germany) was used to record the eye movement trajectories of the participants' primary eye. The sampling frequency was 1250 Hz.

Experimental procedures

The experiment employed a 2 (autistic trait: high AQ vs. low AQ) × 2 (cue sociality: gaze cues vs. dot cues) × 2 (cue validity: valid vs. invalid) three-way mixed design, in which the autistic trait was the between-subjects factor, while cue sociality and cue validity were the within-subjects factors.

The participant sat approximately 72 cm away from the screen and was asked to read the instructions. After practicing and familiarizing with the experimental procedure, they proceeded to the formal experiment. The experimental procedure is shown in Fig. 1. First, a fixation point was presented for 500 ms. Then, two irregular polygons were presented simultaneously on the left and right sides of the screen as memory items for 250 ms. After a blank screen interval of 500 ms, the eyes or dots were presented in the center of the screen for 500 ms. Then, the eyes or dots were shifted 0.8° to the left or right and presented for 500 ms as gaze or dot cues. After a 500 ms interval, a polygon appeared on the left or right side of the screen for 3000 ms as a probe. The participant was asked to judge whether the

probe was the same as the memory item presented at the same location, and to respond using the left and right mouse buttons. The participant was asked to respond as quickly and as accurately as possible. Before the experiment began, the participant was told that the validity of the cue was related to the location at which the target appeared at the probe interface and the cue validity was 50%. The formal experiment consisted of 192 trials: two blocks with 96 trials in each block. One block was the social cue condition, and the other was the non-social cue condition. The order of the two blocks was counterbalanced across the participants, and the participants could take a break once every 48 trials. The eye movement trajectories of the participant's primary eye were recorded simultaneously using an eye tracker. Before starting the experiment, the participant's primary eye was measured, adjusted, and calibrated so that the eye movement deviation was within 1°.

Figure 1. Experimental paradigm

Data collection and processing

One participant was removed because their accuracy was beyond three standard deviations (accuracy, 44.20%), and the eye-tracking data for this participant were also removed. Trials with incorrect responses were removed from the RT analysis, and incorrect trials accounted for 19.6% of the total trials. In the analysis of the eye-tracking data, two equally sized regions of interest (ROIs) were defined according to the locations on the left and right sides of the screen where the memory items and probes appeared, which occupied 6.50% of the screen area. The eye-tracking data corresponded to behavioral errors at each interface, and data without any fixation points on the interfaces were removed (accounting for 21.83% of the total data on the encoding interface, 21.56% on the cue interface, 20.80% on the post-cue blank screen, and 20.38% on the probe interface). To control for the effects of attention level, four participants with a tracking ratio of less than 60% were removed. One participant's eye movement trajectories deviated too substantially, such that the data in the encoding and probe interfaces were both zero, and hence were deleted. Forty participants were finally included in the eye-tracking data analysis, including 21 participants in the high autistic trait group and 19 participants in the low autistic trait group. All data were analyzed using SPSS 19.0.

For the analysis of RT and accuracy, a 2 (autistic trait: high AQ vs. low AQ) × 2 (cue sociality: gaze cues vs. dot cues) × 2 (cue validity: valid vs. invalid) repeated measures analysis of variance (ANOVA) was performed. Greenhouse-Geisser correction was used to adjust the degrees of freedom for the ANOVAs that did not pass the test of sphericity.

In the analysis of eye-tracking data, with reference to previous studies [8, 38, 39] and considering the experimental paradigm of the present study, we analyzed eye-tracking data separately for the encoding interface (memory items presentation phase), cue interface, post-cue blank screen, and probe phase, using the metrics detailed below.

The indicators of the encoding interface included (1) first fixation duration of the memory item: an early indicator for the attentional processing of the memory items; (2) fixation time of the memory items:

reflecting the attentional processing of the memory items.

Indicators of the cue interface included (3) percentage of accurate gaze shifts: the ratio between the number of trials in which the participant saccaded to the cued ROI and the total number of trials in which the participant saccaded to the left and right ROIs; (4) percentage of fixation time: the ratio between the total fixation time on the cued/uncued ROI and the total fixation time on the interface; and (5) fixation counts: the sum of the number of fixations made by each participant on the cued/uncued ROI under each condition represents their fixation preference.

Indicators of the post-cue blank screen included (6) percentage of fixation time: the ratio of the total fixation time on the cued/uncued ROI to the total fixation time on the interface; (7) fixation counts: the sum of the number of fixations by each participant on the cued/uncued ROI in each condition.

Indicators of the probe interface included (8) percentage of first gaze shifts: the ratio between the number of trials in which the participant's first saccade was made to the cued/uncued ROI and the total number of trials in which they saccaded to either ROI after the presentation of the probe interface; (9) Entry time into the target ROI: the time from the presentation of the probe interface to the first entry into the target ROI, i.e., the time taken for their attention to shift to the target stimulus. A shorter duration indicates a faster attentional shift. (10) First and total fixation times to the target ROI.

For indicator (3) above, a 2 (autistic trait: high AQ vs. low AQ) × 2 (cue sociality: gaze vs. dot) repeated measures ANOVA was performed. For indicators (1) and (2), a 2 (autistic trait: high AQ vs. low AQ) × 2 (visual field: left vs. right) repeated measures ANOVA was performed. For indicators (4), (5), (6), (7), and (8), a 2 (autistic trait: high AQ vs. low AQ) × 2 (cue sociality: gaze vs. dot) × 2 (cue congruence: cued vs. uncued ROI) repeated measures ANOVA was performed. For indicators (9) and (10), a 2 (autistic trait: high AQ vs. low AQ) × 2 (cue sociality: gaze vs. dot) × 2 (cue validity: valid vs. invalid) repeated measures ANOVA was performed. Greenhouse-Geisser correction was performed to adjust the degrees of freedom for ANOVAs that did not pass the sphericity test, and Bonferroni correction was performed for post hoc comparisons.

Results

The results of RT and accuracy

The RT results indicated that the difference between the autism trait groups was not significant, $F(1, 43)$ = 0.70, $p = 0.41$, $\eta p^2 = 0.02$. The main effect of cue validity was significant, $F(1, 43) = 8.92$, $p = 0.005$, $\eta p^2 = 0.17$, 95% CI = [− 72.25, − 14.01], such that RT under valid cues was significantly lower than under invalid cues. The interaction effect among autistic traits, cue validity, and cue sociality was significant, $F(1, 43) = 8.63$, $p = 0.005$, $\eta p^2 = 0.17$. The simple effects test found that the low-AQ group showed significantly lower RT for valid gaze cues compared to the RT for invalid gaze cues ($p = 0.001$, 95% CI = [− 162.21, − 47.96]) but did not differ significantly between valid and invalid dot cues ($p = 0.28$). The high-AQ group did not differ significantly between valid and invalid cues for both dot ($p = 0.08$) and gaze cues ($p = 0.71$).

None of the other conditions showed significant differences ($p > 0.05$). The accuracy did not show any significant main effects or interactions. The RT and accuracy for each condition are shown in Fig. 2.

Figure 2. RT and accuracy of the high- and low-AQ groups under various conditions

Eye-tracking results

Eye-tracking indicators for the encoding interface

Statistical results of the first fixation duration for the encoding interface showed significant differences between the autistic trait groups, $F(1, 38) = 4.36$, $p = 0.044$, $\eta p^2 = 0.10$, 95% CI = [0.45, 28.96], with the high-AQ group having a significantly higher first fixation duration than the low-AQ group. The main effect of visual field was significant, ($F[1, 38] = 11.05$, $p = 0.002$, $\eta p^2 = 0.23$, 95% CI = [15.55, 64.01]), and the first fixation duration was significantly greater for memory items on the left than on the right. The differences were not significant in any of the other conditions $(p > 0.05)$.

The statistical results for total fixation time showed a significant difference between the autistic trait groups, $F(1, 38) = 4.52$, $p = 0.04$, $\eta p^2 = 0.11$, 95% CI = [0.77, 31.35]. This was significantly greater for the high-AQ group than for the low-AQ group. The visual field main effect was significant, $F(1, 38) = 11.11$, $p = 0.002$, $\eta p^2 = 0.23$, 95% CI = [16.77, 68.64], and the total fixation time was significantly greater for memory objects on the left than on the right. The difference was not significant in any of the other conditions $(p > 0.05)$.

Eye-tracking indicators for the cue interface

The statistical results for the percentage of accurate gaze shifts showed that there were no significant main effects or interactions $(p > 0.05)$.

The statistical results for the percentage of fixation time on the ROI showed significant differences between the autistic trait groups, $F(1, 38) = 4.85$, $p = 0.034$, $\eta p^2 = 0.11$, 95% CI = [0.005, 0.12], with the high-AQ group showing a significantly larger percentage of fixation time than the low-AQ group. This difference was not significant for any of the other conditions $(p > 0.05)$.

The statistical results on the fixation counts for the ROI showed that the difference between the autistic trait groups was marginally significant, $F(1, 38) = 4.10$, $p = 0.05$, $\eta p^2 = 0.10$, 95% CI = [− 0.008, 15.31], with the high-AQ group showing a trend toward a larger fixation count on the ROI than the low-AQ group. There was a significant main effect of cue congruence, $F(1, 38) = 8.62$, $p = 0.006$, $\eta p^2 = 0.19$, 95% CI = [1.01, 5.49], and the total fixation counts were significantly greater for cued than for uncued ROIs.

Eye-tracking indicators for the post-cue blank screen

The statistical results for the percentage of fixation time showed that the difference between the autistic trait groups was not significant, $F(1, 38) = 2.28$, $p = 0.139$. The cue congruence main effect was significant, $F(1, 38) = 20.17$, $p < 0.001$, $\eta p^2 = 0.35$, 95% CI = [0.06, 0.17], with cued ROIs showing a

significantly greater percentage of fixation time than uncued ROIs. The three-way interaction among cue congruency, between-group factors, and cue sociality was marginally significant, $F(1, 38) = 3.47$, $p = 0.07$, $\eta p^2 = 0.084$. For gaze-uncued ROIs, the percentage of fixation time was significantly greater in the high-AQ group than in the low-AQ group ($p = 0.001$, 95% CI = [0.05, 0.18]), whereas for dot-uncued ROIs, the difference between the two groups did not reach a significant level ($p = 0.082$). The high-AQ group had a significantly greater percentage of fixation time for dot-cued ROIs than for uncued ROIs ($p = 0.035$, 95% CI = [0.006, 0.15]), but the difference between gaze-cued and uncued ROIs was not significant ($p = 0.16$). The low-AQ group showed a significantly greater percentage of fixation time for gaze-cued ROIs than for uncued ROIs ($p < 0.001$, 95% CI = [0.11, 0.30]), and that for dot-cued ROIs was also significantly larger than uncued ROIs ($p = 0.005$, 95% CI = [0.04, 0.19]). The low-AQ group showed a significantly smaller percentage of fixation time for gaze-uncued ROIs than for dot-uncued ROIs ($p = 0.037$, 95% CI = [− 0.10, − 0.003]), but the difference between gaze-cued ROIs and dot-cued ROIs was not significant ($p = 0.167$). None of the other conditions showed significant differences ($p > 0.05$).

The statistical results for fixation counts indicated that the difference between the autistic trait groups was not significant, $F(1, 38) = 1.63$, $p = 0.209$. The cue congruency main effect was significant, $F(1, 38) = 21.65$, $p < 0.001$, $\eta p^2 = 0.36$, 95% CI = [8.65, 21.96], with the fixation counts for cued ROIs being significantly greater than those for uncued ROIs. The main effect of cue sociality was marginally significant, $F(1, 38) = 3.35$, $p = 0.075$, $\eta p^2 = 0.08$, 95% CI = [− 0.34, 6.85], showing a trend toward greater fixation counts for ROIs under gaze cues. There was a significant interaction effect between cue sociality and cue congruency, $F(1, 38) = 4.87$, $p = 0.033$, $\eta p^2 = 0.11$, whereby the fixation counts for gaze-cued ROIs were significantly greater than those for uncued ROIs ($p < 0.001$, 95% CI = [10.72, 27.51]), while that for dot-cued ROIs was also significantly greater than that for uncued ROIs ($p = 0.001$, 95% CI = [4.96, 18.03]). In terms of cued ROIs, the fixation counts for the gaze condition were significantly greater than for the dot condition ($p = 0.019$, 95% CI = [1.22, 12.90]). In contrast, for uncued ROIs, the difference between the gaze and dot conditions was not significant ($p = 0.78$). The three-way interaction between cue congruency, between-group factors, and cue sociality was marginally significant, $F(1, 38) = 3.52$, $p = 0.068$, $\eta p^2 = 0.085$. For gaze-uncued ROIs, the high-AQ group had significantly higher fixation counts than the low-AQ group ($p = 0.003$, 95% CI = [5.13, 23.57]), while gaze-cued ROIs did not differ significantly between the two groups ($p = 0.695$). The high-AQ group had significantly higher fixation counts for dot-cued ROIs than for dot-uncued ROIs ($p = 0.047$, 95% CI = [0.13, 18.15]), but the difference between the gaze-cued and uncued ROIs was not significant ($p = 0.08$). The low-AQ group had significantly greater fixation counts for gaze-cued ROIs than for uncued ROIs ($p < 0.001$, 95% CI = [15.79, 40.11]) and dot-cued ROIs compared to uncued ROIs ($p = 0.005$, 95% CI = [4.37, 23.31]). The low-AQ group showed significantly greater fixation counts for gaze-cued ROIs than for dot-cued ROIs ($p = 0.018$, 95% CI = [1.85, 18.78]), whereas the difference between gaze-uncued and dot-uncued ROIs was not significant ($p = 0.196$). None of the other conditions displayed significant differences ($p > 0.05$).

Eye-tracking indicators for the probe interface

The statistical results of the percentage of first gaze shifts showed a significant main effect of cue congruency, $F(1, 38)$ = 19.90, $p < 0.001$, ηp^2 = 0.34, 95% CI = [0.10, 0.28], with a significantly greater percentage of first gaze shifts to cued ROIs than to uncued ROIs. The interaction between cue congruency and cue sociality was significant, $F(1, 38)$ = 5.30, p = 0.027, ηp^2 = 0.12. Under gaze cues, the percentage of first gaze shifts to cued ROIs was significantly larger than to uncued ROIs ($p < 0.001$, 95% CI = [0.15, 0.34]). Under dot cues, the percentage of first gaze shifts was significantly greater for cued ROIs than for uncued ROIs (p = 0.009, 95% CI = [0.04, 0.24]). For cued ROIs, the percentage of first gaze shifts under gaze cues was significantly greater than that under dot cues (p = 0.027, 95% CI = [0.006, 0.10]), while for uncued ROIs, the percentage of first gaze shifts under gaze cues was significantly smaller than that under dot cues (p = 0.027, 95% CI = [− 0.10, − 0.006]). The interaction between cue congruency, between-group factors, and cue sociality was significant, $F(1, 38)$ = 6.91, p = 0.012, ηp^2 = 0.15. For gaze-cued ROIs, the percentage of first gaze shifts was significantly greater for the low-AQ group than for the high-AQ group (p = 0.019, 95% CI = [0.02, 0.21]), whereas for gaze-uncued ROIs, the percentage for the low-AQ group was significantly smaller than for the high-AQ group (p = 0.019, 95% CI = [− 0.21, − 0.02]). The difference between the two groups was not significant for dot-cued (p = 0.907) or dot-uncued ROIs (p = 0.907). The high-AQ group showed a significantly larger percentage of first gaze shifts for dot-cued ROIs compared to that for uncued ROIs (p = 0.045, 95% CI = [0.003, 0.28]), while the difference between gaze-cued and uncued ROIs was not significant (p = 0.052). The low-AQ group had a significantly greater percentage of first gaze shifts for gaze-cued ROIs than for gaze-uncued ROIs ($p < 0.001$, 95% CI = [0.22, 0.49]), while the difference between the dot-cued and dot-uncued ROIs was not significant (p = 0.078). The low-AQ group showed a significantly greater percentage of first gaze shifts for gaze-cued ROIs than for dot-cued ROIs (p = 0.002, 95% CI = [0.05, 0.18]), and a significantly smaller percentage for gaze-uncued ROIs than for dot-uncued ROIs (p = 0.002, 95% CI = [− 0.18, − 0.05]). The high-AQ group did not show a significant difference between gaze-cued and dot-cued ROIs (p = 0.814) or between gaze-uncued and dot-uncued ROIs (p = 0.814). None of the other conditions showed significant differences ($p > 0.05$). The gaze trends for the cue interface, post-cue blank screen interface, and probe interface are shown in Fig. 3.

Figure 3. Fixation patterns of the high- and low-AQ groups at different interfaces

The statistical results on the entry time into the probe interface ROI showed no significant difference between the autistic trait groups, $F(1, 38)$ = 0.13, p = 0.723. The main effect of cue validity was significant, $F(1, 38)$ = 13.65, p = 0.001, ηp^2 = 0.26, 95% CI = [− 59.84, − 17.48], whereby the entry time under valid cues was significantly smaller than under invalid cues. The interaction between autistic trait groups and cue validity was marginally significant, $F(1, 38)$ = 3.99, p = 0.053, ηp^2 = 0.10, the entry time for the low-AQ group was significantly lower in the valid condition than in the invalid condition ($p < 0.001$, 95% CI = [− 90.25, − 28.86]), whereas the difference in the high-AQ group was not significant (p = 0.23). The interaction between cue validity and cue sociality was significant, $F(1, 38)$ = 5.71, p = 0.022, ηp^2 = 0.13, and entry time under the valid gaze condition showed a trend toward being lower than the valid dot condition (p = 0.06, 95% CI = [− 40.80, 0.88]), whereas the difference between the gaze and dot-invalid conditions was not significant (p = 0.176). The entry time was significantly lower in the valid gaze condition than in the invalid condition ($p < 0.001$, 95% CI = [− 85.92, − 28.89]), whereas the difference

between the valid and invalid dot conditions was not significant ($p = 0.105$). The interaction between autistic traits, cue validity, and cue sociality was significant, $F(1, 38) = 5.60$, $p = 0.023$, $\eta p^2 = 0.13$; in the valid gaze condition, the entry time for the low-AQ group showed a trend toward being smaller than that of the high-AQ group (marginally significant, $p = 0.053$, 95% CI = [− 0.48, 77.24]). In contrast, in the valid dot condition, the difference between the low and high AQ groups was not significant ($p = 0.598$). In the invalid gaze condition, the entry time was significantly greater for the low-AQ group than for the high-AQ group ($p = 0.027$, 95% CI = [76.25, 4.83]), whereas in the invalid dot condition, the difference between the low and high AQ groups was not significant ($p = 0.680$). The low-AQ group had significantly less entry time under the valid gaze condition than under the invalid gaze condition ($p < 0.001$, 95% CI = [− 138.20, − 55.55]), whereas the low-AQ group did not differ significantly between the valid and invalid dot conditions ($p = 0.208$). The low-AQ group showed significantly less entry time under valid gaze cues than under valid dot cues ($p = 0.036$, 95% CI = [− 62.69, − 2.28]), and significantly greater entry time under invalid gaze cues compared to invalid dot cues ($p = 0.028$, 95% CI = [4.85, 79.45]). In all other conditions, the differences were not significant ($p > 0.05$). See Fig. 4 for more details.

Figure 4. Entry time into the target ROI of the high- and low-AQ groups under various conditions

In terms of the first fixation time for the targets, none of the conditions showed significant differences ($p > 0.05$). The statistical results of the total fixation time on the target object showed significant differences between the high and low AQ groups, $F(1, 38) = 5.49$, $p = 0.024$, $\eta p^2 = 0.13$, 95% CI = [18.47, 253.29], whereby the total fixation time on the probes was significantly greater for the high-AQ group than for the low-AQ group. None of the other conditions showed significant differences ($p > 0.05$).

Discussion

The present study primarily used eye-tracking techniques in conjunction with behavioral experiments to carry out a paradigm that combined cueing with change detection tasks and set 50% valid cues for different levels of sociability. We aimed to investigate the mechanisms underlying the influence of autistic traits on JA and whether this influence further altered individuals' visual working memory performance. The ηp^2 values in our results of main effects and interaction effects with significant p-values were all 0.10 and above. Based on the criteria defined by Lenhard and Lenhard [40], the effect sizes were moderate and above, indicating that the results were relatively reliable.

Gaze is a distinctive social cue that plays an important role in communicating the intentions of others and forming joint attention [41]. Previous research has found that gaze has unique sociality and attracts individuals to exhibit more gaze-following behaviors [5, 6]. The present study found that the low-AQ group had shorter memory RT to probes at the cued location in the valid gaze condition compared to the invalid gaze condition. Eye-tracking data from 500 ms after cue presentation to probe presentation showed that the low-AQ group was more likely to fixate at gaze-cued locations, while the high-AQ group was less likely to use gaze cues and tended to use dots as attentional cues. Regarding the percentage of first gaze shifts at the probe interface, the low-AQ group showed a significantly higher percentage of first gaze shifts to

gaze-cued ROIs than to dot-cued ROIs, whereas the high-AQ group did not show a significant difference between gaze-cued and dot-cued ROIs. Furthermore, the percentage of first gaze shifts to gaze-cued ROIs was significantly higher in the low-AQ group than in the high-AQ group. In terms of the entry time into the probe ROI, the low-AQ group took a shorter time to attend to the probe in the valid gaze condition. These results suggest that even with 50% cue validity, the low-AQ group tended to follow eye-gaze for attentional shifts and used gaze cues to detect target stimuli, whereas the high-AQ group tended to rely on non-socially meaningful dot cues and was deficient in gaze-directed JA. A study of young children at high risk for autism (high familial risk of autism) found that high-risk infants showed more correct saccades when both head and eyes were turned toward the object than when only the eyes were turned toward the object, whereas low-risk infants did not differ in the correct saccades between the two conditions. This suggests that high-risk infants relied more on cues other than gaze cues to respond [9]. During social interactions, individuals with high levels of autistic traits looked less into the experimenter's eyes than individuals with low levels of autistic traits [23]. An electroencephalogram study of a spatial cue task also found that higher AQ scores resulted in a lower cost to incongruence attentional processing caused by gaze cues (smaller P2 amplitude for incongruent minus congruent trials) [42]. These studies suggest that individuals with high autistic traits are less sensitive to gaze, which is more socially meaningful, and thus have deficiencies in gaze-induced social attention.

The eye-tracking results showed in greater detail the changes in the relationship between cue effects and autistic traits over time in the cue, post-cue blank screen, and probe interfaces. Within 500 ms of cue presentation, the high and low autistic trait groups showed no difference in their attentional preference for cued locations, regardless of whether the cue was gaze or dots. During the 500 ms of the post-cue blank screen, the low-AQ group showed a higher percentage of fixation time and higher fixation counts on the cued location for both gaze and dot cues. The high-AQ group showed a higher percentage of fixation time only for dot-cued locations. In the subsequent probe interface, the percentage of first gaze shift in the low-AQ group to the gaze-cued ROI was significantly higher than to the gaze-uncued ROI, while in the high-AQ group, the percentage of first gaze shift to the dot-cued ROI was significantly higher than to the dot-uncued ROI. In terms of entry time to the ROI, the low-AQ group only had a shorter entry time in the valid condition for gaze cues, while the high-AQ group did not show cue facilitation in the valid condition for either gaze or dot cues. These results suggest that within 500 ms of cue presentation, the eye movements of individuals were mainly influenced by cue congruence, and autistic traits did not modulate the cueing effects. However, after 500 ms, the autistic trait level modulated the cueing effects for different cues. The low-AQ group was more sensitive to gaze cues and more likely to use gaze cues to direct their attention to the cued location. Therefore, the faster speed at shifting attention to the probe resulted in a shorter RT on the working memory task. In addition, the comparison between gaze cues and dot cues suggests that the differences between the high and low autistic trait groups were due to the sociality of the cues rather than the low levels of iris or pupil movement. These results suggest that autistic traits affect individuals' JA after 500 ms of cue presentation. Furthermore, for individuals with low autistic traits, gaze has a unique significance, eliciting stronger and longer-lasting cue effects. For individuals

with high autistic traits, the unique meaning of gaze was reduced, and participants showed a preference for non-social cues. This between-group difference can further affect RT in working memory tasks.

The present study found that the high and low autistic trait groups showed different patterns of eye movements over time during the early and subsequent periods of cue presentation. The cueing effect was predominantly present during the 500 ms of cue presentation, and the interaction between autistic traits and cues was only evident after 500 ms of cue presentation. This pattern of change suggests that the rapid, automatic reflexive attention shown in the early stage is more sensitive to the orientation directed by the cue but may not distinguish the sociality conveyed by the cue. In contrast, voluntary attention appears later and lasts longer [43, 44], at which point it is more likely to be influenced by other factors such as the properties of the cue and the individual characteristics. Previous researchers have debated whether gaze-induced attention is a form of reflexive or top-down voluntary attention [43, 45]. The results of this study suggest that gaze-induced cueing effects appear to be indistinguishable from non-social cues early on, but are more likely to direct top-down voluntary attention in the later stages and can be modulated by autistic traits. Due to limitations of the experimental parameters defined in this study, in which we explored changes in the eye-tracking indicators before and after the 500 ms boundary, future research could further refine the sociality of cues and their early effects on autistic traits within 500 ms of cue presentation.

In addition, many studies have found that for peripheral cues, when the SOA is around 300 ms, the RT for the cued target is significantly longer than for the uncued target, that is, the inhibition of return (IOR), whereas the cueing effect of central cues is longer in duration and IOR occurs later, especially for gaze cues [46, 47]. Frischen and Tipper [48] found that the IOR was only exhibited under gaze cues when the SOA was 2400 ms. Yoxon et al. [49] also used a 50% validity gaze cue and set up seven SOAs: 100, 250, 400, 700, 1000, 1700, and 2400 ms. They found that at SOAs of 250, 400, 700, and 1000 ms, significant cueing effects were observed. In contrast, the differences between cued and uncued targets were not significant in the 100, 1700, and 2400 ms SOA conditions. This study used a central cue with an SOA of 1000 ms and found that even with a cue validity of only 50%, individuals with low autistic traits would intrinsically orient their attention toward the location indicated by the gaze cue for a relatively long duration. Therefore, their attention could have been engaged more quickly in the target of the probe interface when the gaze cue was valid. In contrast, the high-AQ group was less likely to follow gaze and less likely to use gaze cues to shift attention. Although they showed an attentional preference for non-socially cued locations, the duration was short and thus did not exert a cueing effect in terms of the entry time into the target ROI. The different patterns of eye movement between the two groups further suggest that individuals with high autistic traits have reduced sensitivity to gaze, and their characteristics of JA are different from those in the low autistic trait population.

From the working memory RT data, we can observe the same trend as for the entry time into the target ROI. That is, individuals with high levels of autistic traits are less sensitive to the social intentions expressed by gaze and show less gaze following behaviors. Therefore, the speed of their attentional shifts to the target ROI is not affected by gaze cues, resulting in similar results for visual working memory

RT. It is important to note that the effect of social attention on working memory in this study was reflected only in RT and did not affect the accuracy of the memory. This is not entirely consistent with the findings of Nie et al. [30] on the effect of social cues on working memory. They also set cues with 50% validity and found that memory performance was better with valid social cues than with invalid social cues, while dot cues did not show a cueing effect on memory performance. This indicates that social cues can modulate the maintenance of working memory content. Compared with this study, the pictures used by Nie et al. [30] were faces with different gaze orientations. Faces have been found to produce strong interference with cognitive tasks [50]. Relative to the gaze in this study, faces would have produced a stronger interference on the participants' working memory, resulting in the need to rely on social cues to maintain memory content. This may be why memory performance was not affected by the validity of gaze cues in this study. In addition, the present study did not find a difference in working memory performance between the high- and low-AQ groups. However, it could be seen from the eye movements that the high-AQ group had a longer fixation time for the memory objects and probes. This may have been because the high-AQ group was more attracted to local information about the polygons. Research has shown that individuals show preferences and memory advantages for global processing in working memory [51]. However, as AQ scores increase, participants show decreased global processing of the target and increased local processing, and they pay more attention to processing details [52]. It is possible that the high- and low-AQ groups use different processing strategies during memory processes that can affect their memory performance. This needs to be further explored in the future.

Limitations

This study has several limitations. First, although the sample size calculated by G*power was sufficient and the effect sizes reported were acceptable for this study, participants in our study were recruited from one university, and all of them were undergraduate or graduate students, which limits the generalizability of our findings to individuals in the general population. In addition, six irregular polygons were selected as memory items in this study. The small number of items may have resulted in a relatively simple memory task and may have led participants to encode polygons into long-term memory, which may have changed the initial experimental design of visual working memory and affected memory performance. In future studies, the effects of autistic trait-related differences in JA on visual working memory should be further investigated by increasing the memory load and defining different cue validities. Attention training for individuals with high autistic traits may also be an effective way to improve social attention and promote healthy physical and mental development.

Conclusions

The present study combined a cueing paradigm, change detection task, and eye-tracking techniques, and found that autistic traits dynamically modulate the effect of gaze cues on individuals' JA. Individuals with low autistic traits were more adept at using gaze cues, with stronger and longer-lasting gaze-elicited cueing effects, while individuals with high autistic traits were less sensitive to gaze cues and preferred

non-social cues. This difference in JA affected the speed at which the visual working memory tasks were completed.

Abbreviations

ANOVA
Analysis of variance
AQ
Autism-Spectrum Quotient
ASD
Autism Spectrum Disorders
IOR
Inhibition of return
JA
Joint attention
RJA
Reflexive joint attention
VJA
Voluntary joint attention
ROI
Regions of interest
RT
Reaction time

Declarations

Ethics approval and consent to participate: Ethical approval of the study was granted by the Anhui Normal University Ethics Committee. Informed consent was obtained from all participants.

Consent for publication: Not applicable.

Availability of data and materials: The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing interests: The authors declare that they have no competing interests.

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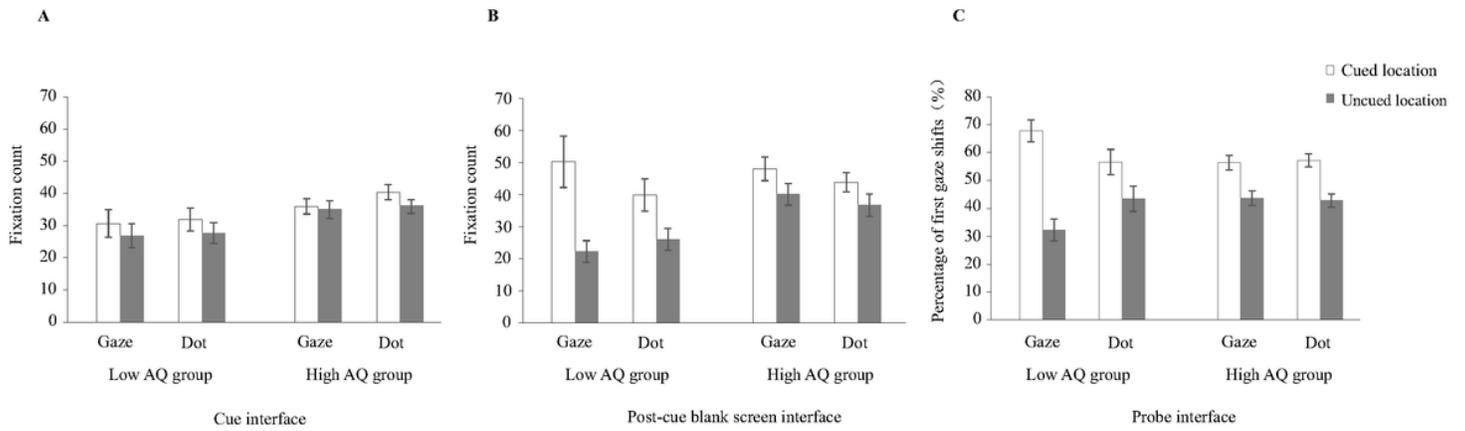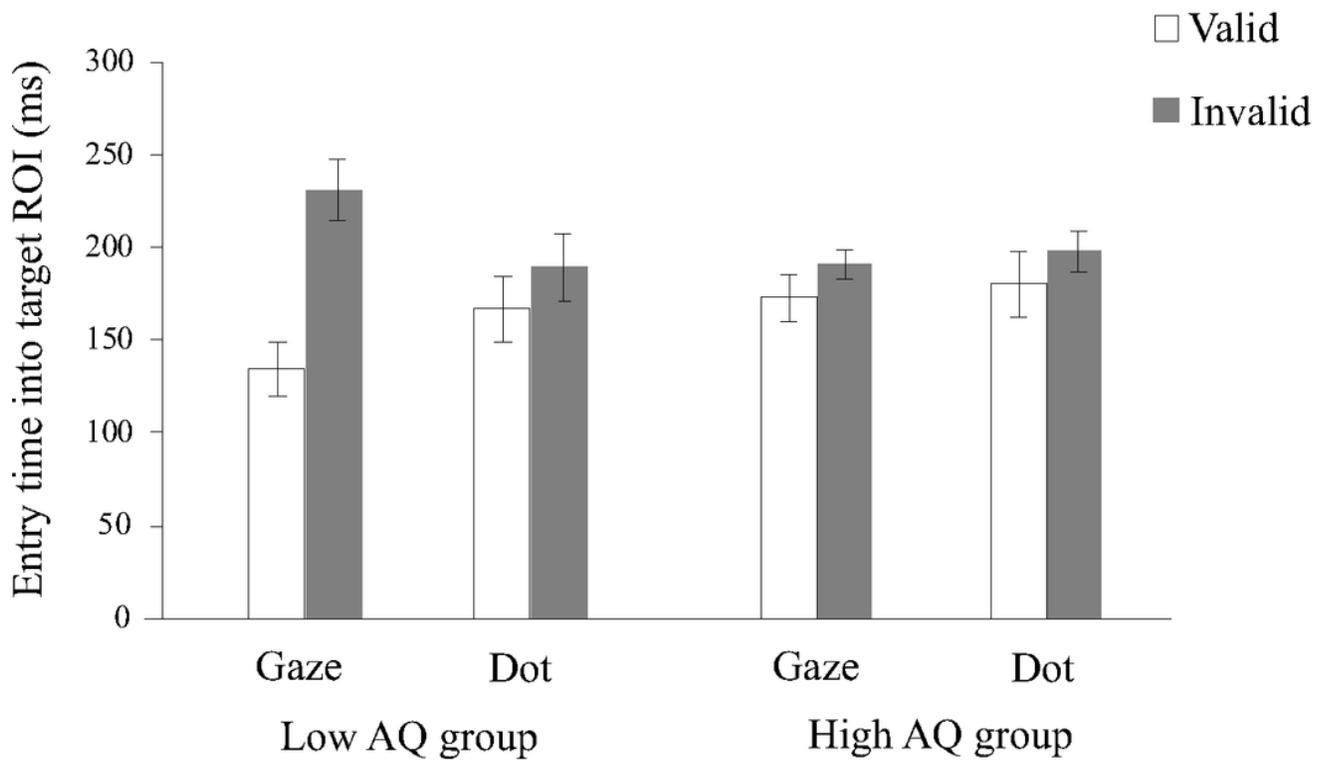
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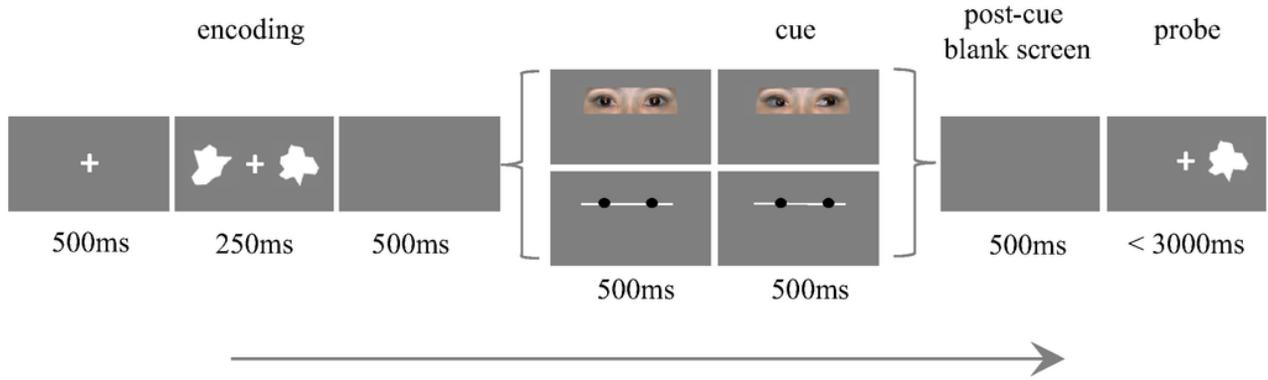
Figure 1

Experimental paradigm
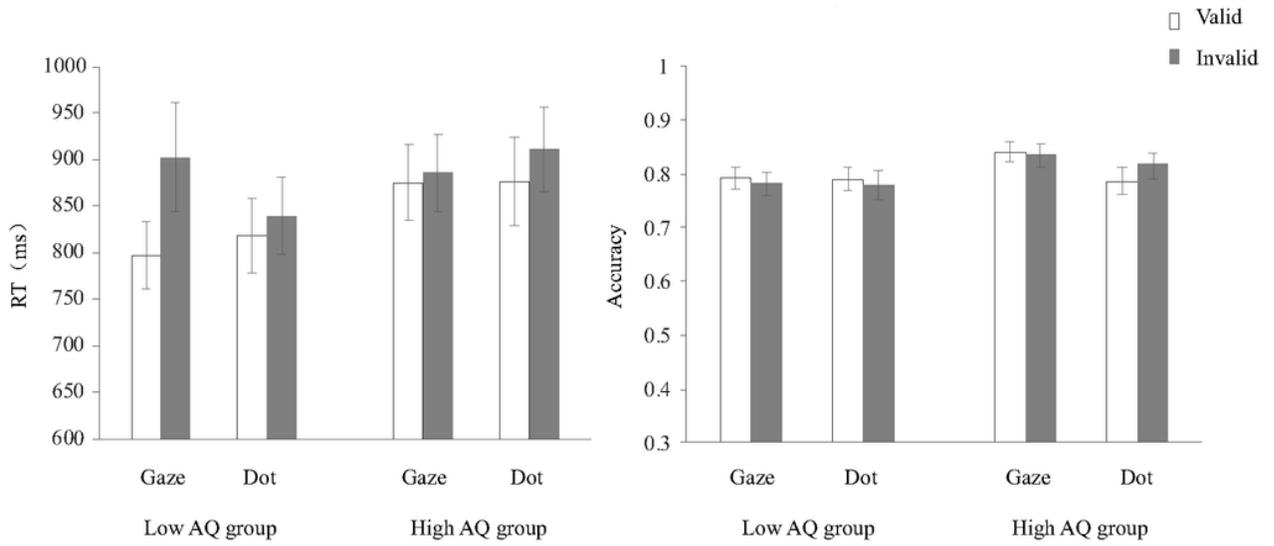
Figure 2

RT and accuracy of the high- and low-AQ groups under various conditions

Figure 3

Fixation patterns of the high- and low-AQ groups at different interfaces

Figure 4

Entry time into the target ROI of the high- and low-AQ groups under various conditions