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Gaze-Triggered Communicative Intention Compresses Perceived Temporal Duration

Yiwen Yu[1,2,3], Li Wang[1,2,3], and Yi Jiang[1,2,3]
[1]State Key Laboratory of Brain and Cognitive Science, Institute of Psychology, Chinese Academy of Sciences; [2]Department of Psychology, University of Chinese Academy of Sciences; and [3]Chinese Institute for Brain Research

Abstract
Eye gaze communicates a person's attentional state and intentions toward objects. Here we demonstrate that this important social signal has the potential to distort time perception of gazed-at objects ($N = 70$ adults). By using a novel gaze-associated learning paradigm combined with the time-discrimination task, we showed that objects previously associated with others' eye gaze were perceived as significantly shorter in duration than the nonassociated counterparts. The time-compression effect cannot be attributed to general attention allocation because it disappeared when objects were associated with nonsocial attention cues (i.e., arrows). Critically, this effect correlated with observers' autistic traits and vanished when the gazing agent's line of sight was blocked by barriers, reflecting the key role of intention processing triggered by gaze in modulating time perception. Our findings support the existence of a special mechanism tuned to social cues, which can shape our perception of the outer world in time domains.

Keywords
eye gaze, time perception, social cue, arrow cue, intention

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Human eyes, as "windows to the soul," can indicate the whereabouts of others' focus of attention and communicate the potential behavior intentions of other individuals (Frischen et al., 2007). It has been well documented that humans are especially sensitive to eyes, with a tendency to orient their own attention following others' eye gaze (Shepherd, 2010). Such ability, known as *social attention*, plays a crucial role in social interaction and nonverbal communication (Nummenmaa & Calder, 2009). By adopting a now widely used central cuing paradigm, researchers revealed that nonpredictive eye gaze cues could reflexively shift the observers' attention to the gazed-at location (Birmingham & Kingstone, 2009; Driver et al., 1999; Friesen & Kingstone, 1998). Moreover, the function of eye gaze extends beyond guiding attention. It has been shown that gaze cues have the power to transfer the intentionality of a person onto the object being looked at. Such *intentional imposition* enriches the object with properties that it would not display if not looked at (Manera et al., 2014; van der Weiden et al., 2010). For instance, observers preferred the objects that fell under others' gaze (Bayliss et al., 2006; Madipakkam et al., 2019; Ulloa et al., 2015). Besides, gaze boosted working memory performance of the gazed-at objects, but only when shared intentionality was possible between the observer and the agent who delivered gaze (Gregory & Jackson, 2019). In sum, the mentalizing aspect of gaze holds a unique power to influence how we perceive and process objects in the environment (Capozzi & Ristic, 2020).

Gaze not only exerts influences on the cognitive processes mentioned above (e.g., attention, working memory), but it also possesses the capability to impact time perception. For instance, direct gaze, which has the potential to signal the intention to interact (rather than simple motion), compressed time perception (Burra & Kerzel, 2021; Jarick et al., 2016; but see Thönes & Hecht, 2016). Besides, intentional gaze, which would lead to social consequences (i.e., having others follow the gaze), induced an underestimation of the temporal gap between the saccades and the outcomes (Stephenson et al., 2018). Such a temporal-underestimation effect

Corresponding Author:
Li Wang, Institute of Psychology, Chinese Academy of Sciences
Email: wangli@psych.ac.cn

disappeared when an eye movement was made only in a nonsocial context. These temporal illusions have adaptive function, as they may offer chances to fully engage and prepare oneself for the upcoming social interaction (Burra & Kerzel, 2021; R. Liu et al., 2018; Stephenson et al., 2018). The aforementioned findings on intention-evoked temporal illusion give rise to a question of whether the time perception of the gazed-at objects could be influenced in a similar fashion to that of the gaze itself.

According to the coding-efficiency account (Eagleman & Pariyadath, 2009), subjective time perception of the stimulus is linked to the strength of neural encoding activity. That is, when less energy is used to encode the stimulus, a shorter time is perceived (Eagleman & Pariyadath, 2009; Noguchi & Kakigi, 2006). It is relevant to note that gaze facilitates the processing of cued objects in young infants (Reid & Striano, 2005). The cued objects were processed more effectively, whereas the uncued objects required further processing, which is evidenced by enhanced neural activity triggered by the uncued objects when compared with the cued ones (Wahl et al., 2013). Importantly, this enhanced processing effect is highly specific to gaze but not nonsocial cues (Michel et al., 2019; Wahl et al., 2013). On the basis of these findings, it is reasonable to hypothesize that objects consistently gazed at by others might result in compressed time perception.

To probe this issue, the present study adopted a novel gaze-associated learning paradigm adapted from a previous study (Bayliss et al., 2006). In this paradigm, the association between the direction of a central gaze cue and the spatial locations of two targets was systematically manipulated during the learning phase. Specifically, one target would consistently associate with the gaze direction, and the other would not. To investigate whether gaze-associated learning changes the time perception of the targets, we employed a duration-discrimination task before and after the learning phase in which participants were asked to compare the presentation duration of two stimuli. We further examined the role of the intention processing in the obtained time-distortion effect by utilizing arrows or blocked gaze as central cues, which can trigger similar attentional effects but without intentionality (Bayliss et al., 2006; Cole et al., 2015; Gregory & Jackson, 2019; Manera et al., 2014). As for the targets, faces (Experiments 1 and 2) and Gabor patches (Experiments 3 through 6) were selected to examine whether the gaze-induced time-distortion effect, if observed, can be extended from high-level socially relevant stimuli to low-level elementary visual stimuli. In Experiment 6, we also measured participants' autism-spectrum quotient (AQ) scores (Baron-Cohen, Wheelwright, Skinner, et al., 2001; Zhang et al., 2016) to take account of individual differences in social proficiency (e.g., ability with intentional processing; Baron-Cohen, Wheelwright, Hill, et al., 2001; R. Liu et al., 2018; Nummenmaa et al., 2012).

Statement of Relevance

Our experience of time is not the authentic representation of physical time and can be distorted by the properties of the stimuli. In this research, we report a novel temporal illusion: that eye gaze, being a crucial social cue, can distort subjective time perception of unchanged objects. Specifically, adult participants compared the duration of two objects before and after they had implicitly seen that one object was consistently under gaze whereas the other object was never under gaze. We found that gaze-associated objects were perceived as having a shorter duration than nonassociated ones. This effect was driven by intention processing elicited by social cues, as nonsocial cues (i.e., arrows) and blocked gaze failed to induce such time distortions. Notably, individuals lower in autistic traits showed greater susceptibility to gaze-induced time distortions. This research highlights the role of high-level social function in time perception. Time flies faster when observers are confronted with objects that fell under others' gaze.

Method

Participants

One hundred and eighty university students (113 females) aged between 18 and 32 (M = 22.6 years, SD = 2.7 years) were recruited in six experiments via an online advertisement. Twenty-four (12 females) participated in Experiment 1, 24 (13 females) in Experiment 2, 22 (13 females) in Experiment 3, 22 (12 females) in Experiment 4, 40 (26 females) in Experiment 5, and the remaining 48 (37 females) in Experiment 6. All participants had normal or corrected-to-normal vision and gave written informed consent in accordance with procedures and protocols approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences. They were all naive to the purpose of the experiments. A two-tailed power analysis using G*Power (Version 3.1.9.7; Faul et al., 2007) indicated that a sample size of at least 17 participants would afford 95% power to detect a high gaze-induced effect (Cohen's d = 0.94), which was found in a previous study with a similar design (Bayliss et al., 2006). We have further increased the sample size per experiment to adequately detect the potential effects in the current study. We excluded participants whose data-fitting R^2 value either in the pretest or in the posttest was less than 75%. Only one participant in Experiment 3 was excluded from further analysis for this reason. We also excluded participants who did not believe in the setting of the barrier at all in Experiment 5 (n = 5, 3 females).

Stimuli

Stimuli were generated and displayed using MATLAB (The MathWorks, Natick, MA) together with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) on a 19-in. CRT monitor (1,280 × 1,024 at 60 Hz). All stimuli were presented within a white frame (17.9° × 17.9°) on a gray background (RGB value = 128, 128, 128), and the viewing distance was about 57 cm. Four faces (subtended approximately 6.8° × 8.5° in visual angle) taken from volunteers (2 females) with neutral expressions were used as central cues in Experiment 1, Experiment 3, Experiment 5 and Experiment 6. The eye regions and pupils of each face were manipulated in Adobe Photoshop to create faces with gaze averted to the left or right. A black arrow (1.1° × 0.8°) served as a central cue in Experiment 2 and Experiment 4. Two different cartoon faces (2.0° × 2.7°) were used as the target stimuli in Experiment 1 and Experiment 2. Cartoon images were used because they allow for greater control over the visual features of the stimuli and minimize potential confounding factors that may arise from using real images (e.g., gender and race), therefore avoiding possible biases or emotions that might be associated with real images. Horizontal and vertical Gabor patches (2.3° × 2.3°) were employed as the target stimuli in Experiment 3, Experiment 4, and Experiment 5. Tilted (tilted 45° toward the left or tilted 45° toward the right) and vertical Gabor patches (2.3° × 2.3°) were utilized as the target stimuli in Experiment 6.

Procedure

Experiment 1 was composed of three phases: pretest phase, gaze-associated learning phase, and posttest phase (see Fig. 1). Participants completed a duration-discrimination task in both the pretest and posttest phases. In the duration-discrimination task, each trial began with a white cross (0.6° × 0.6°) presented in the center of the screen for 1,000 ms. After that, two different cartoon faces were displayed in the center of the screen in sequence with an interstimulus interval (ISI) that varied between 400 ms and 600 ms. One of the cartoon faces was randomly selected as the standard stimulus and was presented for 500 ms, and the other could be displayed for 200, 300, 400, 500, 600, 700, or 800 ms, creating seven test conditions. The difference of the presentation durations between the two stimuli could be from −300 ms to 300 ms in steps of 100 ms. The presentation order of the two stimuli was randomized. Participants were asked to determine which stimulus (the first or the second) appeared longer regardless of the contents and presentation order of the stimuli and entered their responses by pressing the left or the right arrow key on the keyboard. Each participant completed a total of 140 trials (20 trials for each test condition). The trials were presented in a randomized order for each participant.

The gaze-associated learning phase started with fixation on a central cross for 1,000 ms. Then a face looking straight ahead appeared in the center for 1,000 ms, and right after that, the eyes looked left or right for 300 ms. After a 100 ms ISI, a cartoon face serving as the target stimulus appeared on the left or right of the screen (4.5° horizontally away from the center). The target stimulus remained on the screen until a response was made. Participants were instructed to indicate the location (left or right) of the target as quickly and accurately as possible by pressing the left or right arrow key on the keyboard, respectively. Note that the direction of eye gaze was not predictive of the location of the target. In particular, systematic contingency was arranged between the gaze cue and the cartoon target. Specifically, one of the cartoon faces was always displayed in the same direction of gaze cues (associated condition), and the other constantly appeared on the opposite side (nonassociated condition). Which cartoon face would be consistently associated with the gaze cues was balanced across participants. Participants were not told about this contingent cue-target association. The learning phase contained 128 trials with 64 associated trials and 64 nonassociated trials.

The localization task was selected in the present study because of its moderate difficulty level and its ability to elicit a substantial gaze-cuing effect (McKay et al., 2021). It should be pointed out that previous studies investigating the power of gaze in influencing object evaluation have employed both the localization task (Madipakkam et al., 2019) and the discrimination task (Bayliss et al., 2006) in the gaze-cuing paradigm. Both studies have consistently shown that gaze has a positive impact on object evaluation (Bayliss et al., 2006; Madipakkam et al., 2019), suggesting that task types employed in the gaze-cuing paradigm might not be a decisive factor for the gaze-liking effect.

Experiment 2 followed a similar design and procedure as Experiment 1, except that leftward or rightward arrows were employed as central cues in the learning phase and they were presented for 300 ms. Experiment 3 was identical in structure to Experiment 1 except that horizontal and vertical Gabor patches instead of cartoon faces were used as the target stimuli (see Fig. 2). The procedure of Experiment 4 was identical to that of

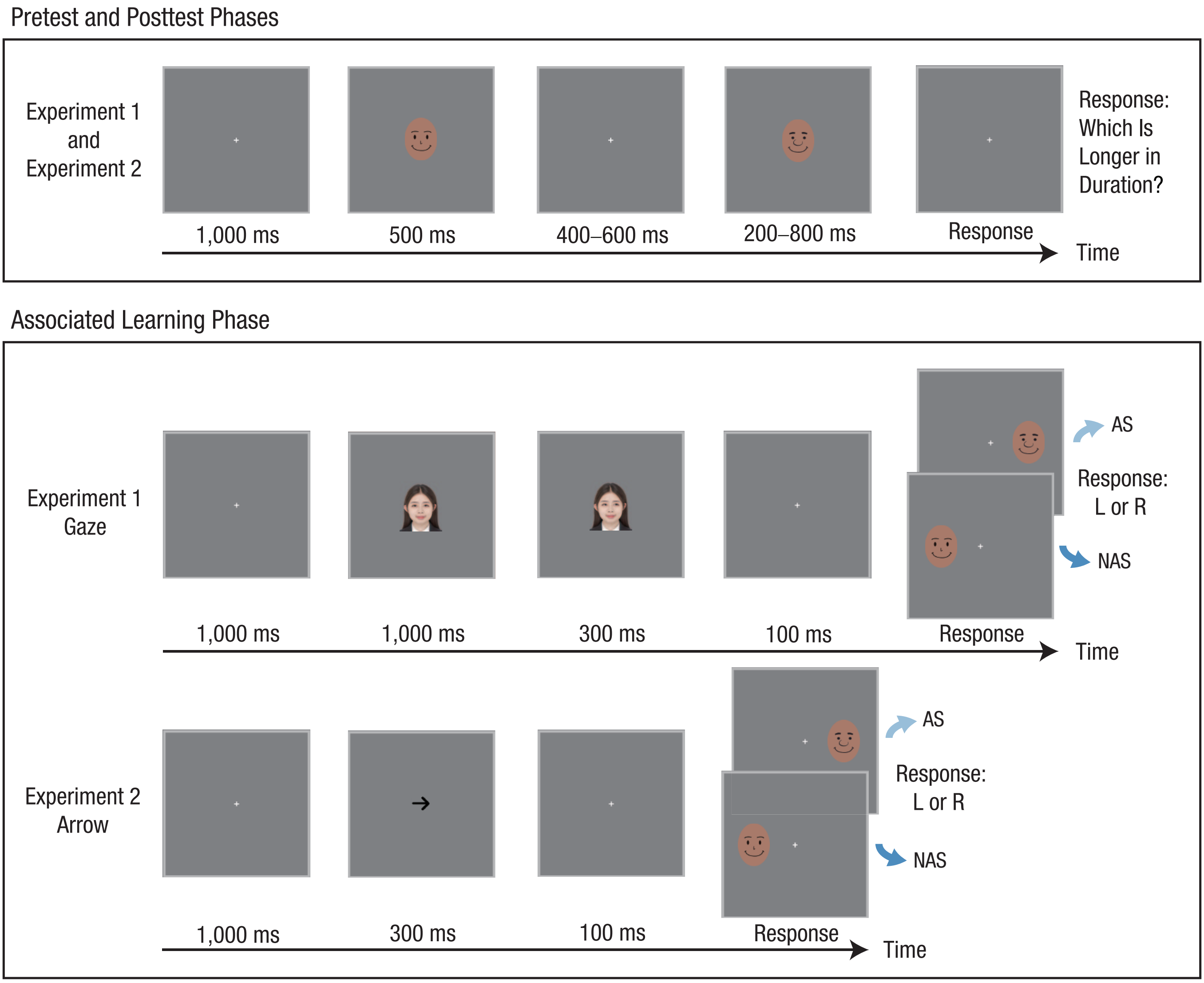

Fig. 1. Schematic representation of the experimental paradigm in Experiments 1 and 2. Both experiments contained three phrases. Participants first completed a duration-discrimination task as the pretest. Then participants completed a modified central cuing task in the learning phase, during which a certain cartoon face would always appear on the side indicated by the central cues (gaze cues in Experiment 1, arrow cues in Experiment 2; associated condition). Another cartoon face would always appear on the opposite side from that indicated by the central cues (nonassociated condition). Which cartoon face would be consistently associated with the central cues was balanced across participants. Finally, participants completed the duration-discrimination task as the posttest. The photographs of the cuing agent were exclusively utilized for illustrative purposes and were not among the four faces employed in the experiments. AS = associated; NAS = nonassociated.

Experiment 2 except that horizontal and vertical Gabor patches were used as the target stimuli.

Experiment 5 had a similar procedure to Experiment 3 except that in the learning phase the gaze cues were flanked by the barrier stimuli on both sides. The barriers consisted of two rhombus shapes (3.0° × 15.0° each, 4.2° horizontally away from the center), made to have a three-dimensional appearance, which fit between the face and the Gabor patch (6.3° horizontally away from the center). Before the learning phase began, participants were given the instruction that the barriers blocked the agent's line of sight. After the three phases ended, there were follow-up questions to check participants' beliefs about the effectiveness of the barriers. Participants who expressed complete disbelief in the function of the barriers were excluded from the analysis (see the Participants section).

In Experiment 6, we added a novel stimulus (which was not the target in the learning phase) in the pretest and posttest phases (see Fig. 3). To be specific, participants completed two blocks of the duration-discrimination task in both the pretest and posttest.

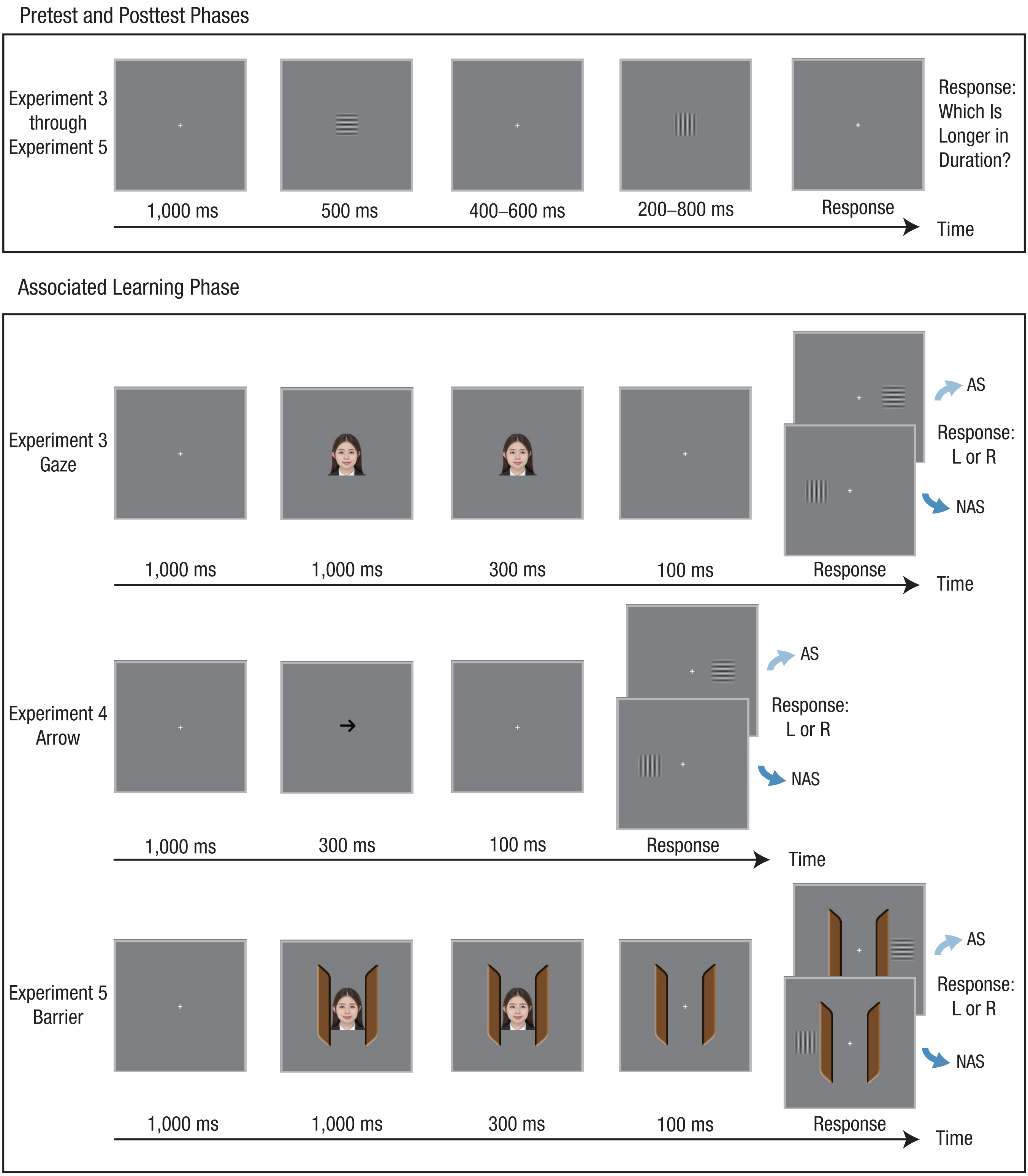

Fig. 2. Schematic representation of the experimental paradigm in Experiments 3 through 5. The experimental procedures were similar to those in Experiments 1 and 2, except that Gabor patches served as the target stimuli. Moreover, in Experiment 5, participants were given the instruction that the barriers blocked the agent's line of sight in the learning phase. The photographs of the cuing agent were exclusively utilized for illustrative purposes and were not among the four faces employed in the experiments. AS = associated; NAS = nonassociated.

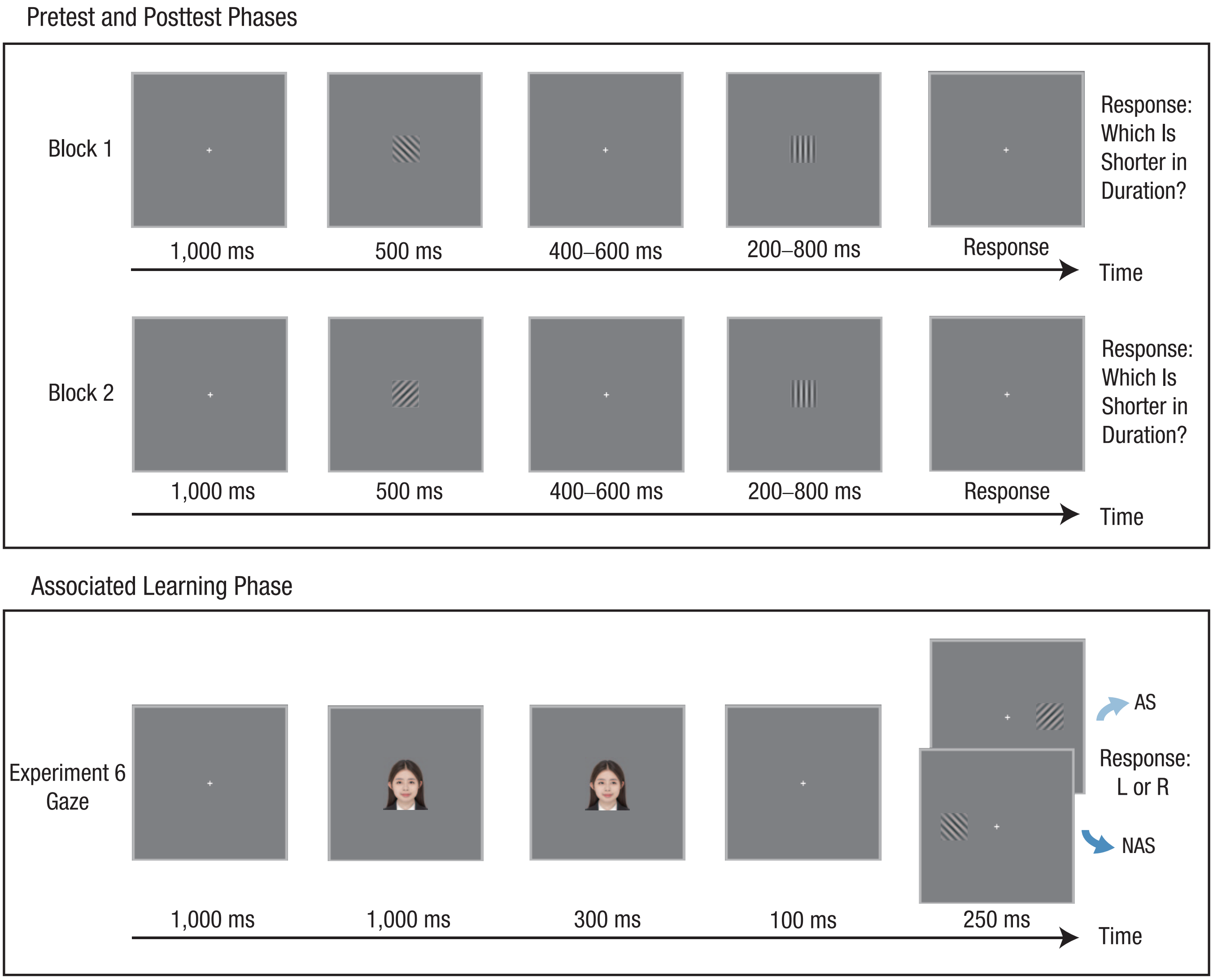

Fig. 3. Schematic representation of the experimental paradigm in Experiment 6. Participants completed two blocks of the duration-discrimination task as the pretest and posttest, where associated and nonassociated Gabor patches were separately compared with the novel vertical Gabor patch (which did not appear in the learning phase). Contrary to previous experiments, participants chose which stimulus is shorter in duration. The experimental procedure of the learning phase was similar to that in Experiment 3 except that the presentation duration of the targets was fixed to 250 ms and the targets were tilted Gabor patches. The photographs of the cuing agent were exclusively utilized for illustrative purposes and were not among the four faces employed in the experiments. AS = associated; NAS = nonassociated.

Each block had a similar design as in Experiment 3, except that stimuli in one block were the associated Gabor patch (tilted 45° toward the left or 45° toward the right) and the novel Gabor patch (vertical), whereas the stimuli in another block were the nonassociated Gabor patch (tilted 45° toward the right or 45° toward the left) and the novel Gabor patch (vertical). Two factors—that is, which Gabor patch would be consistently associated with the gaze cues, and the order of the block—were balanced across participants. To address the concerns about response bias, contrary to the previous experiments, we asked participants to indicate which stimulus had appeared for less time. As for the learning phase in Experiment 6, we restricted the display duration of the targets to 250 ms. Even if participants responded faster than 250 ms, the target remained on until 250 ms has elapsed. The targets in the learning phase were the Gabor patches (tilted 45° toward the left or 45° toward the right). Other stimuli and procedures in the learning phase were the same as in Experiment 3. What is more, we measured participants' autistic traits using a Chinese version of the AQ questionnaire (Baron-Cohen, Wheelwright, Skinner, et al., 2001; Zhang et al., 2016) following the three experimental phases. Higher

AQ scores are indicative of a greater presence of autistic-like traits, which have been associated with reduced or atypical social-cognitive abilities and distinct neural responses to social stimuli (Baron-Cohen, Wheelwright, Hill, et al., 2001; Nummenmaa et al., 2012). Additionally, we included debriefing questions at the end of the study to inquire whether participants were explicitly aware of the gaze-object association.

Results

The statistical analyses of the pretest and posttest tasks in six experiments were based on the *point of subjective equality* (PSE) obtained from fitting a Boltzmann sigmoid function to each individual data point (Wang & Jiang, 2012). The PSE is defined as the point at which participants perceived the two stimuli as equal in terms of the presentation duration. A psychometric curve was drawn for each participant that depicted the proportion of longer responses to the associated stimulus as a function of the differences between the presentation durations of two test stimuli (associated vs. nonassociated). In Experiment 6, in order to be consistent with the previous results, we asked participants to choose the stimulus with the shorter duration, but we actually recorded and analyzed the data as the proportion of the longer response to the associated or nonassociated targets as a function of the differences between the presentation durations of two test stimuli (associated vs. novel or nonassociated vs. novel). In analyses, we transformed the duration differences (from −300 ms to 300 ms in steps of 100 ms) to 1, 2, 3, 4, 5, 6, and 7. A positive shift of PSE from pretest to posttest means that the duration of the associated stimulus was perceived as shorter compared with that of the nonassociated stimulus (i.e., temporal compression) after learning, whereas a negative shift of PSE indicates the reverse (i.e., temporal expansion). In addition, the different limen (DL; half the interquartile range of the fitted function) was used to measure the temporal-discrimination sensitivity.

Experiments 1 and 2: temporal compression specific to gaze-associated but not arrow-associated cartoon faces

In Experiment 1, during the gaze-associated learning phase, participants responded significantly faster to cartoon faces presented at the same location indicated by the gaze direction (associated condition or congruent condition) than to those presented at the opposite location (nonassociated condition or incongruent condition), 340.1 ms versus 353.0 ms, $t(23) = -4.06$, $p < .001$, Cohen's $d = 0.828$, 95% confidence interval (CI) for the mean difference = [−19.5, −6.3], even when the gaze direction did not predict the target location. In other words, a robust gaze-cuing effect was observed in the learning phase, consistent with previous studies (Bayliss et al., 2006; Friesen & Kingstone, 1998; Ji et al., 2020; W. Liu et al., 2021). Following the gaze-associated learning task, the posttest revealed a significant positive shift of PSE compared with that in the pretest, 3.935 versus 4.078, $t(23) = -2.11$, $p = .046$, Cohen's $d = 0.430$, 95% CI for the mean difference = [−0.284, −0.003], indicating a temporal-compression illusion of the cartoon face newly associated with the gaze direction. Moreover, participants' DL was not significantly different between the pretest and posttest, 1.010 versus 0.977, $t(23) = 0.55$, $p = .590$, Cohen's $d = 0.111$, 95% CI for the mean difference = [−0.094, 0.161], which indicates that the time-compression effect was not due to the change of temporal-discrimination sensitivity. Notably, the temporal-compression effect (calculated using the difference in the mean PSE obtained under the posttest versus that under the pretest divided by their sum, $\frac{PSE_{\text{posttest}} - PSE_{\text{pretest}}}{PSE_{\text{posttest}} + PSE_{\text{pretest}}}$) was not significantly correlated with the magnitude of the attentional effect (calculated using the difference in the mean reaction time [RT] obtained under the incongruent condition versus that under the congruent condition divided by their sum, $\frac{RT_{\text{incongruent}} - RT_{\text{congruent}}}{RT_{\text{incongruent}} + RT_{\text{congruent}}}$)($r = .09$, $p = .666$). This result suggests that the attentional effect alone cannot modulate visual time perception of the gaze-associated object.

In Experiment 2, we employed a nonsocial attentional cue (i.e., arrow) to further examine whether the observed temporal illusion was specific to gaze processing. Results showed that nonpredictive arrow cues could also trigger a similar attentional-orienting effect in the learning phase, 359.9 ms versus 367.3 ms, $t(23) = -2.57$, $p = .017$, Cohen's $d = 0.524$, 95% CI for the mean difference = [−13.4, −1.4], which is in line with previous studies (Bayliss et al., 2006; Ristic et al., 2002). Besides, the magnitudes of the attentional effects were not significantly different between the gaze and the arrow cues, $t(46) = 1.34$, $p = .188$, Cohen's $d = 0.386$, 95% CI for the mean difference = [−0.004, 0.020]. In contrast to Experiment 1, there was no significant difference between the PSEs of the pretest and the posttest, 4.082 versus 4.035, $t(23) = 0.64$, $p = .527$, Cohen's $d = 0.131$, 95% CI for the mean difference = [−0.105, 0.199], reflecting that the temporal illusion of the gaze-associated cartoon face

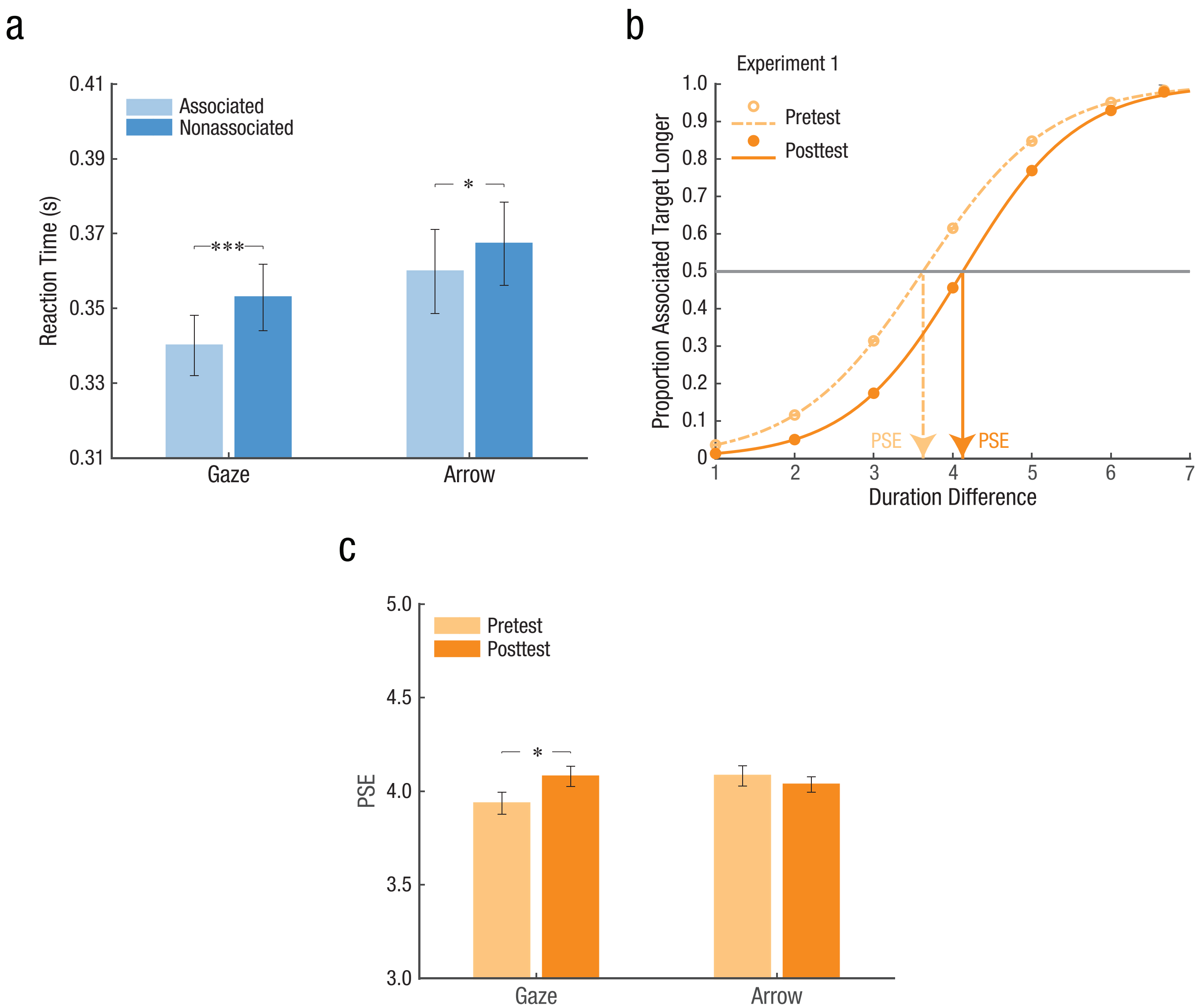

Fig. 4. Results from Experiments 1 and 2. Results from the learning phase are shown in (a). Both gaze and arrow cues induced the attentional effect: Participants responded faster when targets appeared on the side where central cues indicated. A psychometric function for a typical observer is shown in (b). Data are shown for the pretest (dashed curve) and the posttest (solid curve). The proportion of responses in which the participant judged the associated object as longer in duration than the nonassociated one is plotted as a function of the duration difference between the two objects. The point of subjective equality (PSE) difference between the pretest and posttest indicates the change in time perception after the learning phase. In (c) we show results from the pretest and posttest phases: The gaze-associated cartoon face compressed time perception, but the arrow-associated cartoon face did not. Error bars represent standard errors of the mean. $*p < .05$. $***p < .001$.

disappeared when it was associated with arrow direction. Again, the DLs remained unchanged before and after the arrow-associated learning, 0.886 versus 0.959, $t(23) = -1.15$, $p = .262$, Cohen's $d = 0.235$, 95% CI for the mean difference = [−0.206, 0.059]. Collectively, these findings of Experiment 1 and Experiment 2 (see Fig. 4) clearly demonstrated a temporal-compression illusion caused by specific gaze information processing rather than the mere shift of attention.

Experiments 3 and 4: temporal compression specific to gaze-associated but not arrow-associated Gabor patches

To further explore whether the gaze-induced time-compression effect of cartoon faces could be extended to low-level elementary visual stimuli, we adopted Gabor patches instead of cartoon faces in Experiments 3 and 4.

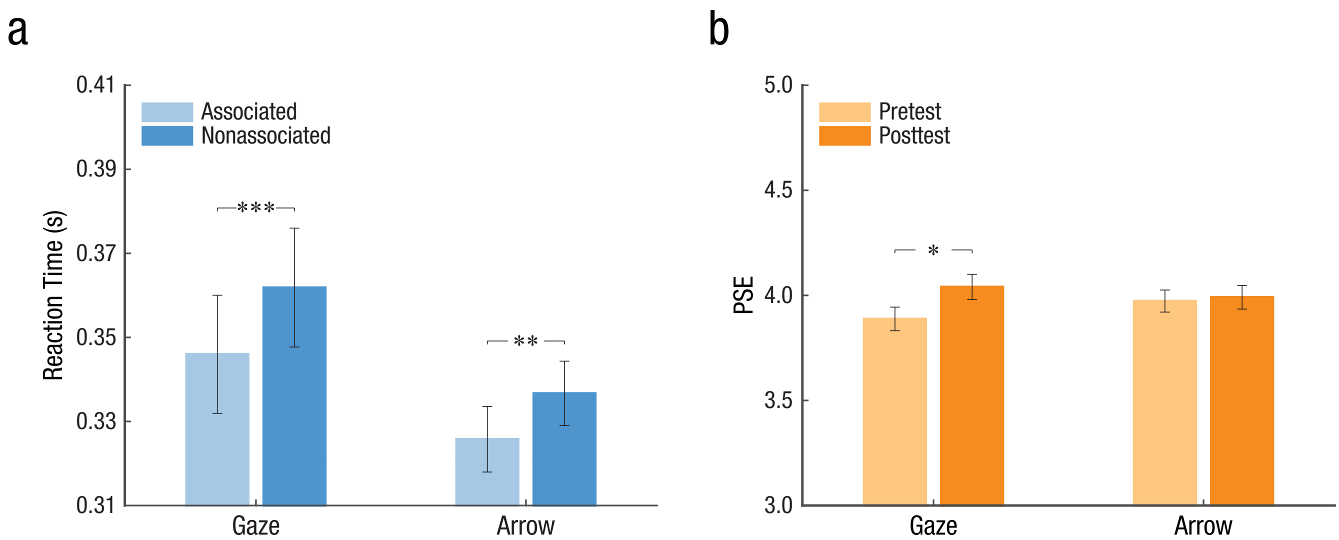

Fig. 5. Results from Experiments 3 and 4. Results from the learning phase are shown in (a): Both gaze and arrow cues induced the attentional effect. Results from the pretest and posttest phases are shown in (b): The gaze-associated Gabor patch compressed time perception after the learning phase, but the arrow-associated Gabor patch did not. Error bars represent standard errors of the mean. PSE = point of subjective equality. $^*p < .05$. $^{**}p < .01$. $^{***}p < .001$.

As expected, we found a significant attentional-orienting effect whether gaze was used as the central cue, 346.0 ms versus 361.9 ms, $t(20) = -5.23$, $p < .001$, Cohen's $d = 1.142$, 95% CI for the mean difference = [−22.2, −9.5], or whether an arrow was used as the central cue, 325.8 ms versus 336.7 ms, $t(21) = -3.06$, $p = .006$, Cohen's $d = 0.652$, 95% CI for the mean difference = [−18.3, −3.5] (see Fig. 5a), replicating Experiments 1 and 2. The attentional effects of gaze and arrow cues again did not differ from each other, $t(41) = 0.88$, $p = .386$, Cohen's $d = 0.267$, 95% CI for the mean difference = [−0.008, 0.019]. Similar to Experiment 1, paired-samples t tests revealed a significant positive shift of PSE (see Fig. 5b, left) in the posttest compared with the pretest in Experiment 3—3.888 versus 4.040, $t(20) = -2.31$, $p = .032$, Cohen's $d = 0.503$, 95% CI for the mean difference = [−0.290, −0.015]—reflecting a temporal-compression effect for the gaze-associated Gabor patch. Moreover, the correlation between the magnitude of the attentional effect and the time-compression effect was not significant ($r = .02$, $p = .934$). Furthermore, this time-compression effect vanished in Experiment 4 (see Fig. 5b, right), where Gabor patches were associated with arrow cues, 3.973 versus 3.991, $t(21) = -0.25$, $p = .804$, Cohen's $d = 0.054$, 95% CI for the mean difference = [−0.168, 0.132], which dovetailed with Experiment 2. Again, no significant change of DLs was observed before and after the learning phase both in Experiment 3, 0.930 versus 1.007, $t(20) = -1.35$, $p = .192$, Cohen's $d = 0.295$, 95% CI for the mean difference = [−0.194, 0.042], and Experiment 4, 0.986 versus 1.049, $t(21) = -0.92$, $p = .371$, Cohen's $d = 0.195$, 95% CI for the mean difference = [−0.208, 0.081]. Additionally, the magnitude of the time-compression effect in Experiment 1 was not different from that observed in Experiment 3, $t(43) = -0.09$, $p = .933$, Cohen's $d = 0.025$, 95% CI for the mean difference = [−0.025, 0.023].

We acknowledged that there is a small inconsistency between the gaze-cuing task and the arrow-cuing task in terms of the presence of apparent motion. To address this concern, we conducted a supplementary experiment in which the arrow-learning phase included a straight line (1,000 ms) followed by a two-headed arrow (300 ms). The results of this experiment were consistent with those of Experiment 4 (see the Supplemental Material available online).

In sum, the time-compression effect could be generalized from socially relevant cartoon faces to low-level elementary Gabor patches, revealing a robust and general modulation of gaze-associated learning on time perception.

Experiment 5: temporal compression caused by the intentionality of perceived gaze

On the basis of the results mentioned above, we inferred that the reason why gaze-associated learning specifically induced the time-compression effect is that gaze cues, rather than arrow cues, could stimulate intention processing. To test this hypothesis, we conducted Experiment 5 in which the agent's line of sight was blocked by the barriers. It has been demonstrated that this manipulation

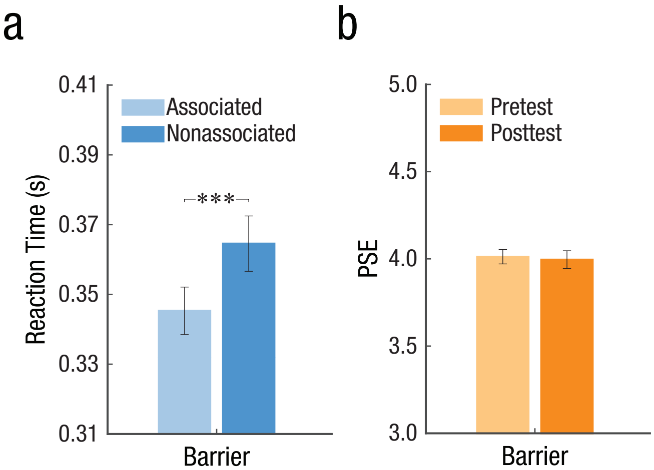

Fig. 6. Results from Experiment 5. Results from the learning phase are shown in (a): Gaze cues with the barriers induced the attentional effect. Results from the pretest and posttest phases are shown in (b): The time-compression effect disappeared when the intentionality of the gaze cue was disrupted. PSE = point of subjective equality; error bars represent standard errors of the mean. $^{***}p < .001$.

can disrupt the intentionality of gaze cues (Cole et al., 2015; Gregory & Jackson, 2019; Manera et al., 2014). We also examined participants' beliefs about the effectiveness of the barriers and excluded five participants from further analysis who completely did not believe in the setting of the barriers. Interestingly, results showed a significant attentional-orienting effect (see Fig. 6a) evoked by gaze cues even with the presence of the barriers, 345.3 ms versus 364.6 ms, $t(34) = -6.94$, $p < .001$, Cohen's $d = 1.173$, 95% CI for the mean difference = [−24.9, −13.6]. Moreover, there was no significant difference in the attentional effects between the blocked experiment (Experiment 5) and the nonblocked experiment (Experiment 3), $t(54) = 0.69$, $p = .495$, Cohen's $d = 0.190$, 95% CI for the mean difference = [−0.008, 0.015]. However, we found no temporal illusion effect (see Fig. 6b) when the agent's line of sight was blocked: PSEs remained unchanged from the pretest to the posttest, 4.012 versus 3.995, $t(34) = 0.31$, $p = .759$, Cohen's $d = 0.052$, 95% CI for the mean difference = [−0.094, 0.127]. Importantly, the PSE effect $\left(\frac{PSE_{\text{posttest}} - PSE_{\text{pretest}}}{PSE_{\text{posttest}} + PSE_{\text{pretest}}}\right)$ from Experiment 5 is significantly different from that of Experiment 3—Experiment 5 versus Experiment 3: −0.003 versus 0.019, $t(54) = -2.02$, $p = .048$, Cohen's $d = 0.558$, 95% CI for the mean difference = [−0.043, −0.0002]. Again, participants' DL was not significantly different between the pretest and posttest in Experiment 5—0.950 versus 0.963, $t(34) = -0.27$, $p = .788$, Cohen's $d = 0.046$, 95% CI for the mean difference = [−0.114, 0.087]. In conclusion, these results together with Experiments 1 through 4 converged upon the view that the intentionality of perceived gaze plays a key role in modulating time perception, thereby supporting the intention-processing hypothesis.

Experiment 6: temporal-compression effect and its association with autistic traits

To validate that the above results indeed represent temporal compression of the associated objects rather than temporal expansion of the nonassociated objects (or a combination of both), we conducted Experiment 6, in which a novel object was introduced in the pretest and posttest but not in the learning phase. Importantly, participants' social proficiency was taken into account by assessing their AQ.

Results from Experiment 6 revealed a significantly negative correlation (see Fig. 7a) between the standardized PSE effect (posttest PSE effect, $\frac{PSE_{\text{associated}} - PSE_{\text{nonassociated}}}{PSE_{\text{associated}} + PSE_{\text{nonassociated}}}$, minus pretest PSE effect, $\frac{PSE_{\text{associated}} - PSE_{\text{nonassociated}}}{PSE_{\text{associated}} + PSE_{\text{nonassociated}}}$) and AQ scores ($r = -.41$, $p = .004$). Specifically, in the associated condition, there was a significantly negative correlation between the PSE effect $\left(\frac{PSE_{\text{posttest}} - PSE_{\text{pretest}}}{PSE_{\text{posttest}} + PSE_{\text{pretest}}}\right)$ and AQ scores ($r = -.42$, $p = .003$), but not in the nonassociated condition ($r = .15$, $p = .294$). On the basis of the median AQ score (21 in this sample), we split the participants into the low-AQ group (AQ scores ≤ 21, $N = 25$, 18 females) and the high-AQ group (AQ scores > 21, $N = 23$, 19 females).

A 2 (stimulus type: associated vs. nonassociated) × 2 (test condition: pretest vs. posttest) × 2 (AQ group: low-AQ group vs. high-AQ group) mixed-design analysis of variance of PSE results revealed a significant three-way interaction, $F(1, 46) = 6.14$, $p = .017$, $\eta_p^2 = .118$. In the high-AQ group, there was a significant main effect of test condition, $F(1, 22) = 4.45$, $p = .046$, $\eta_p^2 = .168$, with the posttest condition ($M = 3.825$, $SD = 0.298$) showing lower PSE than the pretest condition ($M = 3.916$, $SD = 0.273$). The main effect of stimulus type, $F(1, 22) = 0.07$, $p = .796$, $\eta_p^2 = .003$, and the interaction between stimulus type and test condition, $F(1, 22) = 1.36$, $p = .255$, $\eta_p^2 = .058$, were not significant. This general temporal expansion in the posttest compared with the pretest may be attributed to increased familiarity with the stimuli (Eagleman & Pariyadath, 2009), considering that the novel objects appeared only in the pretest and posttest, whereas the associated objects and nonassociated objects appeared in all three phases. In the low-AQ group, the main effect of stimulus type, $F(1, 24) = 0.76$, $p = .392$, $\eta_p^2 = .031$, or test condition, $F(1, 24) = 0.92$, $p = .347$, $\eta_p^2 = .037$, was not significant.

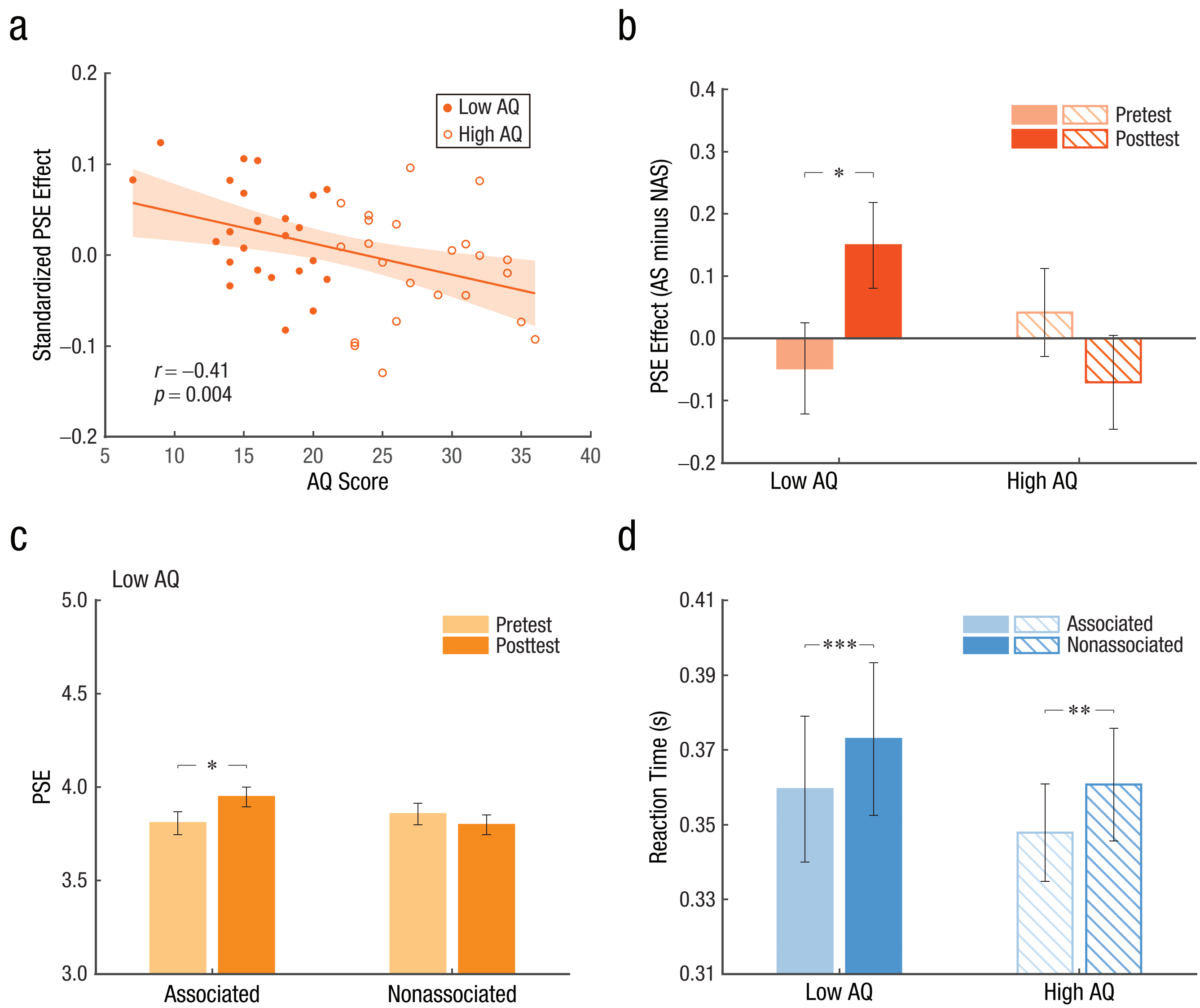

Fig. 7. Results from Experiment 6. The correlation between participants' Autism-Spectrum Quotient (AQ) scores and the standardized PSE effect are shown in (a)—posttest PSE effect, $\frac{PSE_{associated} - PSE_{nonassociated}}{PSE_{associated} + PSE_{nonassociated}}$, minus pretest PSE effect, $\frac{PSE_{associated} - PSE_{nonassociated}}{PSE_{associated} + PSE_{nonassociated}}$. The solid line represents the best-fitting regression. The shaded region reflects the 95% confidence interval. In (b) we show results from the pretest and posttest phases. The time-compression effect was found in the low-AQ group. Results from the low-AQ group (c) indicated that the time-compression effect was driven by temporal compression of the associated objects rather than temporal expansion of the nonassociated objects or a combination of both. In the learning phase (d), the gaze-cuing effect was found in both low- and high-AQ groups. PSE = point of subjective equality; AS = associated; NAS = nonassociated; error bars represent standard errors of the mean. *$p < .05$. **$p < .01$. ***$p < .001$.

However, a significant interaction (see Fig. 7b) between stimulus type and test condition was found, $F(1, 24) = 5.93$, $p = .023$, $\eta_p^2 = .198$, revealing a temporal-compression effect. Further analyses (see Fig. 7c) revealed that the time-perception effect in the low-AQ group was due to temporal compression of the associated stimuli, pretest = 3.808 versus posttest = 3.948, $t(24) = -2.39$, $p = .025$, Cohen's $d = 0.478$, 95% CI for the mean difference = [−0.261, −0.019], and not to temporal expansion of the nonassociated stimuli, pretest = 3.856 versus posttest = 3.798, $t(24) = 0.97$, $p = .343$, Cohen's $d = 0.194$, 95% CI for the mean difference = [−0.065, 0.181].

Importantly, both the low- and high-AQ groups showed significant gaze-cuing effect (see Fig. 7d) in the learning phase—low-AQ group: 359.5 ms versus 372.9 ms, $t(24) = -4.55$, $p \leq .001$, Cohen's $d = 0.910$, 95% CI for the mean difference = [−19.5, −7.3]; high-AQ group: 347.8 ms versus 360.7 ms, $t(22) = -3.66$, $p = .001$, Cohen's $d = 0.763$, 95% CI for the mean difference = [−20.2, −5.6]). Further, there was no significant difference between the magnitudes of the attentional effects $\left(\frac{RT_{\text{incongruent}} - RT_{\text{congruent}}}{RT_{\text{incongruent}} + RT_{\text{congruent}}}\right)$ of the two groups, $t(46) = 0.29$, $p = .770$, Cohen's $d = 0.085$, 95% CI for the mean difference = [−0.010, 0.013].

Therefore, these results demonstrated that gaze shaped time perception by compressing the perceived temporal duration of the gazed-at objects, and this effect was modulated by participants' autistic traits. Importantly, in the debriefing questionnaire, all participants failed to explicitly state the design of the experiment. Therefore, participants were unaware of the actual association between the targets and the gaze cues, and the effect on time perception occurred under the implicit influence of eye gaze.

Discussion

Eye gaze reveals a person's intentions toward objects in the environment. Here we showed that such an important social signal can influence time perception of the object being looked at. Using a gaze-associated learning paradigm combined with the duration-discrimination task, we found that gaze-associated objects compressed time perception compared with nonassociated ones. This gaze-induced time-compression effect can generalize from socially relevant cartoon faces to elementary Gabor patches. Critically, such effects completely disappeared when objects were associated with arrow cues that could induce similar attentional effects, suggesting that the observed temporal illusion was not a mere consequence of attention allocation but involved specific gaze-information processing. Moreover, the temporal illusion relied on the processing of the intentional relation between gaze direction and the object being looked at, as it vanished when gaze cues were blocked by barriers. Notably, the time-distortion effect occurred without participants' explicit awareness of the association between gaze cues and the object, suggesting that the impact of gaze unfolded in an implicit manner. Importantly, the temporal-compression effect exhibited a negative correlation with individuals' autistic traits, with individuals lower in autistic traits showing a greater susceptibility to gaze-induced time distortions, paralleling previous research that has shown a link between shortened subjective duration of social interaction and autistic traits (R. Liu et al., 2018). Together, these findings demonstrate that eye gaze, as an important medium of social interaction, exerts influences beyond guiding spatial attention: It shapes our perception of the outer world in the time domain.

Temporal illusion has also been observed with high-level information (e.g., emotion) processing in previous studies (Droit-Volet & Meck, 2007). However, it has been argued that low-level physical features of emotional stimuli might be confounded with the emotion-induced temporal illusion (Kliegl et al., 2015). Here, the use of gaze-associated objects could overcome potential confounds from low-level perceptual differences, highlighting the role of high-level information processing in time perception (R. Liu et al., 2018). Furthermore, our results demonstrated that the temporal-compression effect relied on intention processing, supporting the notion of *intentional imposition*. When people see others' eyes, they not only follow gaze direction but also transfer onto the gazed-at objects the intentions they read into the eyes of others (Capozzi & Ristic, 2020). This gaze-specific effect of time perception aligns with previous research showing that the gaze-liking effect (Manera et al., 2014) and gaze-boosted working memory effect (Gregory & Jackson, 2019) disappear when the intention processing of gaze was disrupted. The present study extends these findings by reporting a novel temporal illusion mediated by the intentionality of gaze.

Notably, our study provides new evidence on the long-standing debate regarding whether the processing of social cues, compared with nonsocial cues, has distinct mechanisms (for reviews, see Capozzi & Ristic, 2020; Chacón-Candia et al., 2023). The focus of the debate has traditionally been limited to the comparison between gaze cues and arrow cues in triggering attentional orienting and the neural mechanisms that lie behind it (Ji et al., 2020; Ji et al., 2022; W. Liu et al., 2021; Salera et al., 2023). By showing that gaze (but not arrow) has a unique power to shape time perception, we provide a novel angle on the debate. Our results, in conjunction with previous studies demonstrating that eye gaze (but not arrow) influenced affective evaluation and memory of objects (Bayliss et al., 2006; Gregory & Jackson, 2017), support the existence of a specialized mechanism tuned to social cues from a high-level cognitive-function perspective (Chacón-Candia et al., 2023; Wang et al., 2020). Despite the fact that social and nonsocial cues share characteristics of inducing attentional effect, they do guide behaviors distinctly in the contexts where higher-order social-cognitive function, such as intentions, gets involved. Given that our study focused exclusively on eye-gaze cues as social signals, it is crucial for future investigations to explore whether similar temporal distortions can be observed with other types of social signals, such as point-light walkers (Ji et al., 2020; Wang et al., 2020; Yuan et al., 2023). Diversifying the investigation to encompass various social cues can provide a comprehensive understanding of how different social signals influence our perception of time. Additionally, it is worth noting that our study employed computer-based stimuli to present social circumstances. Although this approach allows for precise control over experimental conditions, incorporating real-world activities and interaction in future research would be beneficial to enhance ecological validity, which may better reflect the complexities of social interactions and how temporal processing occurs in natural settings.

What might be the mechanisms behind the gaze-associated time-underestimation effect? From the perspective of internal clock models (for a review, see Droit-Volet & Meck, 2007), attention and arousal can exert opposite effects on time perception. When attention is diverted away from the timing task, time estimation tends to be underestimated, whereas heightened arousal can lead to overestimation of time. Consistent with previous research indicating that gaze cues compressed time perception (Burra & Kerzel, 2021; Jarick et al., 2016), the underestimation of time observed in the present study suggests that objects associated with gaze cues may possess attentional advantages. It is worth noting that another framework can offer alternative insights. By integrating the coding-efficiency account (Eagleman & Pariyadath, 2009) into the predictive-coding framework (Koster-Hale & Saxe, 2013), the obtained underestimation of time can be interpreted as a reflection of efficient representation driven by expectation or prediction (Kok et al., 2012; Otten et al., 2017). Although both frameworks offer potential explanations for the underlying mechanisms in the temporal-compression effect of gaze-associated objects, we acknowledge the necessity for further behavioral and neuroimaging studies to validate either explanation (Koster-Hale & Saxe, 2013).

The modulation of AQ scores on the gaze-induced time-perception effect has important implications for understanding the relationship between gaze processing and autism spectrum disorder (ASD). Impaired social abilities, such as gaze-mediated social attention, are the core features of ASD (Dawson et al., 2012; Mundy, 2018). Surprisingly, laboratory experiments have reported an intact gaze-cuing effect in individuals with ASD (Senju et al., 2004). It has been speculated that compensatory nonsocial strategies might be employed by individuals with ASD to perform the gaze-cuing task (Senju et al., 2004). In our study involving typical individuals, the gaze-cuing effect did not vary on the basis of autistic traits, which is in accordance with previous results. However, we observed a link between higher AQ scores and a diminished temporal-compression effect for gaze-associated targets. This reflected that gaze-mediated temporal effect, which involves higher-order social-cognitive function (i.e., intentions), might serve as a potentially more reliable behavioral marker of ASD. Notably, the temporal-compression effect observed in the present study occurred under the implicit influence of the gaze cues. Our findings hence resonate well with a previous study showing the dissociation between intact explicit, and impaired implicit, social abilities observed in ASD (Senju et al., 2009). Our study, along with previous research, has provided evidence that individuals with more pronounced autistic traits may experience difficulties in spontaneous and implicit intention attribution, which may further hinder their ability to effectively utilize social information for processing objects in the environment (Sevgi et al., 2020). It is important to acknowledge that our study focused solely on typically developing individuals as participants. Further work directly investigating the gaze-mediated temporal effect in clinical samples will help us to gain a better understanding of the relationship between autism, social cognition, and time perception.

In conclusion, the current study clearly demonstrates that gaze cues can implicitly and specifically exert influences on object processing: gaze-associated objects (cartoon face and Gabor patch) compress time perception. This time-compression effect depends on intention processing, as it disappears when objects are associated with arrow or blocked gaze cues. Importantly, such effects can be modulated by individuals' autistic traits. These findings together suggest the existence of a specialized mechanism underlying the processing of social cues and highlight the role of high-level social function in shaping time perception. Time flies faster when observers are confronted with objects that fell under others' gaze.

Transparency

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Yiwen Yu: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing – original draft; Writing – review & editing.

Li Wang: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Software; Supervision; Validation; Writing – review & editing.

Yi Jiang: Conceptualization; Funding acquisition; Methodology; Resources; Software; Supervision; Writing – review & editing.

Declaration of Conflicting Interests

The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

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Open Practices

This study's design and its analysis were not preregistered. All data, analysis code, and research materials generated during the current study have been made available at the Knowledge Repository of Institute of Psychology, Chinese Academy of Sciences (http://ir.psych.ac.cn/handle/311026/42611).

ORCID iDs

Yiwen Yu https://orcid.org/0009-0003-5539-3083
Li Wang https://orcid.org/0000-0002-2204-5192
Yi Jiang https://orcid.org/0000-0002-5746-7301

Supplemental Material

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