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Article

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Intentional looks facilitate faster responding in observers

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Humans construct rich representations of other people's mental states. Here we investigated how intentionality in eye gaze affected perception and responses to gaze. Observers viewed videos of human gazers looking left or right. Unbeknownst to the observers, the gazers could either choose where to look (self-chosen gaze) or were explicitly instructed where to look (computer-instructed gaze). In Experiment 1, observers reported the direction of the gazer's upcoming look before the eye movement was initiated. Faster responses were found for self-chosen relative to computer-instructed gaze. In Experiments 2 and 3, observers responded by reporting the location of a peripheral target that appeared at the gazed-at or not gazed-at location. Faster responses were found for gazed-at relative to not gazed-at targets and at longer cue-target intervals for self-chosen relative to computer-instructed gaze. The examination of the eye movement kinematics indicated that self-chosen gaze shifts were marked by a larger magnitude of motion within the eye region prior to the eye movement occurring relative to computer-instructed ones. Thus, perceived intentionality in eye gaze facilitates responses in observers with the information about mental states communicated via subtle properties of eye motion.

Human interactions require rich representations of other people's attentional and mental states[1,2]. Visual signaling through the non-verbal visuo-communicative system of the eyes, head, and body facilitates rapid communication of social messages covertly without spoken language[3]. Consequently, the ability to follow gaze has been implicated as an important component of both basic and complex social and interactive functions, ranging from joint attention[4] and attitude formation[5] to the computation of social values and status[6]. Despite the ubiquity of gaze for human interactive and social function, there remains a large and important gap in understanding whether the human eyes communicate mental state information[4,7]. Here, we addressed this question in three preregistered experiments using a procedure that enabled us to manipulate the gazer's mental states and to study how the perception of those mental states influenced naïve observers' responses.

Eyes are one of the most salient visual socio-communicative features. Morphologically, the human eye is marked by high visual contrast between the iris and the sclera, which allows for quick and seamless reading of gaze directionality[8,9] and facilitation of a range of social communicative behaviors[2,10–12]. One of the main reasons why it is thought that eye gaze, a term that we use here to denote the percept of eye communication, affects human behavior is because humans spontaneously follow where others are looking[13]. Such gaze-following behavior is theorized to help communicate intentions, mental states, and other social variables to our interactive partners[14,15]. An outstanding question, however, is whether gaze following occurs because of the directional nature of a gaze cue[16,17] or because gaze also signals the gazer's mental state information[18,19]. The literature remains on par, with studies demonstrating both the contribution of directional and mentalistic information to gaze signals, e.g., see ref. 7 for a recent review. Findings in support of the directional account show similar attentional following for gaze and non-social cues like arrows, which convey directionality but not mental states[17,19], while findings in support of the mentalistic account show that gaze following is reduced when the observer believes the gazer cannot see what they are looking at[20] or when the gaze cues are delivered by a non-social agent, like a robot[21].

Here, we approached the question of whether eye gaze conveys mental states from a conceptual angle which allowed us to examine whether mental state information contained within the gaze cue affected observers' perception of that gaze cue and subsequent gaze following response. We did so by filming real individuals making intentional and non-intentional naturalistic eye movements. We followed the design from Pesquita et al.[22], who presented observers with videos of actors reaching for left and right targets. In some trials, the actors chose the target side to reach for, while in other trials, they were instructed which target side to reach for. The observers' task was to indicate the target side the actor would select before they initiated

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their movement. Observers were quicker to identify the targets that the actor endogenously chose as opposed to targets that the actor was instructed to choose. In a similar vein, in our design, we recorded hypothesis-naïve gazers while they looked to the left or right (Fig. 1A). On a random half of the trials, the gazers were instructed to choose to look to either the left or right (i.e., self-chosen trials; intentional gaze). On the other random half of the trials, they were instructed to specifically look to the left or to the right (i.e., computer-instructed trials; non-intentional gaze). In Experiment 1, naïve observers viewed those intentional and non-intentional eye movements and, like in Pesquita et al., were asked to report the direction of the upcoming eye movement before the gazers initiated their gaze shifts. Experiments 2 and 3 examined target-related gaze following responses. In these experiments, two new groups of naïve observers viewed the same eye movement clips but were asked to respond to peripheral targets which were inserted at gazed-at and not gazed-at peripheral locations. If gaze communicates mental states, we expected to find facilitated manual performance for intentional, self-chosen gaze shifts in Experiment 1. Further, if gaze following is affected by perceived mental states in gaze, we expected to find modulations of target-related gaze following in Experiments 2 and 3.

Experiment 1 assessed whether humans were sensitive to the mental state of intentionality within gaze. Observers viewed videos of human gazers making self-chosen (i.e., intentional) and computer-instructed (i.e., non-intentional) left and right eye movements. Before the gaze shift started, each clip was paused, and the observers were asked to indicate the gazer's upcoming eye movement direction (left or right). Intentionality in gaze was manipulated unbeknownst to the observers. If humans were sensitive to the mental state of intentionality in eye gaze, we expected to find facilitated performance for self-chosen compared to computer-instructed trials.

We further reasoned that if observers were sensitive to intentionality information in eye gaze, gaze-following responses should also be affected by such mentalistic information. Experiments 2 and 3 examined this question. The mentalizing account suggests that the intentionality information in self-chosen gaze may lead to greater facilitation (faster RTs) in gazed-at or congruent trials and greater interference (longer RTs) in not-gazed or incongruent trials resulting in larger gaze following magnitude for the self-chosen condition. To test this idea, in Experiment 2, we presented the clips of natural eye movements from Experiment 1 within a modified gaze cuing procedure[13] by asking observers to localize peripheral targets that occurred at either the gazed-at or the not gazed-at location (Fig. 2A). As before, gazers' eye movements were either self-chosen or computer-instructed, and observers remained naïve to this difference. This manipulation enabled us to measure responses to targets that were intentionally looked at by the gazer (i.e., by self-chosen gaze) relative to those that were non-intentionally looked at by the gazer (i.e., computer-instructed gaze). Critically, both conditions included gaze directional information (i.e., eyes looking to the left or right), but only self-chosen trials included additional different information about the gazer's mental state, i.e., intentionality. Thus, if gaze following was influenced by mental states, we expected to find differences in gaze following between the self-chosen and computer-instructed trials. Finally, in Experiment 3, we manipulated the time between the onset of the eye direction cue and the onset of the target between 0 ms (as in Experiment 2), 100 ms, 300 ms, and 700 ms. If mental state information in gaze affects gaze following within the typical time course of activity (i.e., 100–700 ms), we expected to observe a modulation of the gaze following magnitude as a function of cue-target onset time, with the effects unfolding across the 100–700 ms cue-target time window.

Methods

Experiment 1

Participants. Data from 81 undergraduate students recruited via the McGill volunteer undergraduate student participant pool were analyzed (70 women, 11 men, gender reported by participants, mean age = 20.48 years, SD = 1.91, 52% White, 28% Asian/Pacific Islander, 19% Other). An a priori power analysis determined that a sample size of 71 was needed to obtain 80% power (at $\alpha = 0.05$) to detect a small-medium effect size ($d = 0.3$), as reported in ref. 22 and reflecting a difference in Response Time (RT) between self-chosen and computer-instructed trials. The study was preregistered on November 14, 2022, at https://osf.io/qydwk.

As per the preregistration plan, and for all Experiments, response anticipations (RT < 200 ms), timed-out responses (RT > 1800 ms), and data from participants for whom the number of trials after removal of anticipations and timed-out responses was less than 70% of total trials were removed from analyses. Data from 13 participants were removed from analyses based on these preregistered exclusion criteria. All participants reported native English fluency, no history of psychiatric or neurological conditions, and normal or corrected-to-normal vision. Informed consent

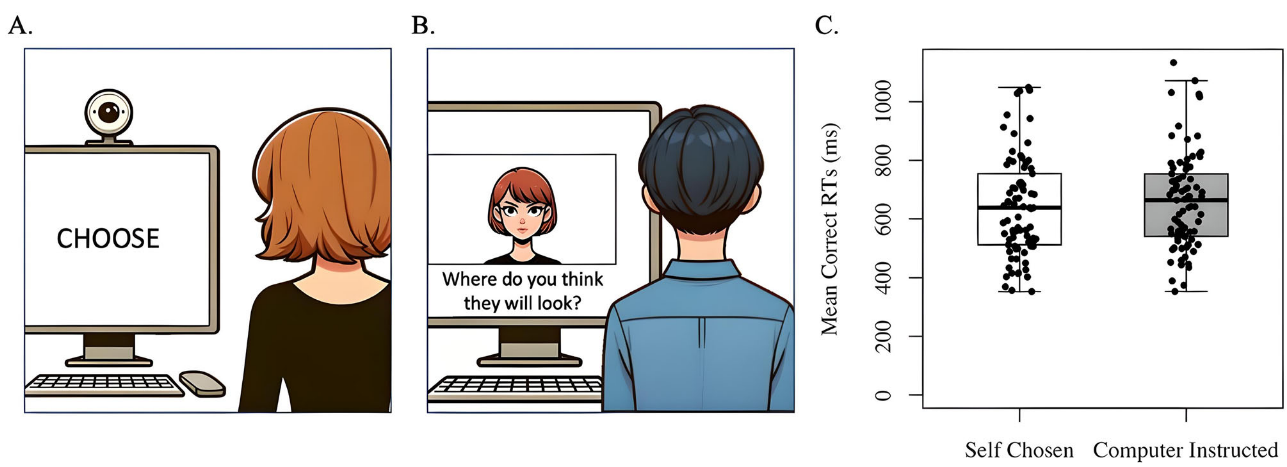

Fig. 1 | Experiment 1 design and results. A Example instruction display for the gazers. Gazers sat in front of a computer screen at an approximate distance of 60 cm with their face and torso filmed using a camera centered on top of the screen. They first saw an instruction for 4000 ms informing them how they should direct their eyes by displaying either 'Choose' or 'Left/Right' message. Next, a peripheral placeholder dot was presented on each left and right side of fixation, and the gazers were instructed to look towards and remain looking at a chosen or instructed location dot for an additional 4000 ms. **B** Example response display for observers. Observers viewed a clip of the gazer making eye movements. The gazer first looked straight ahead for 2000 ms and at T_0 started their eye movement, at which point the video was paused. Observers responded by indicating the direction (left or right) of the gazer's upcoming eye movement. **C** Experiment 1 results. Box plot showing Median Response Time (RT; solid horizontal line) as a function of Gaze intentionality (Self-chosen gaze vs. Computer-instructed gaze; $N = 81$ participants). Boxes encompass data points between the 25th and 75th percentiles, with whiskers indicating the larger minimum value and the smaller maximum value. Points represent individual participant's data.

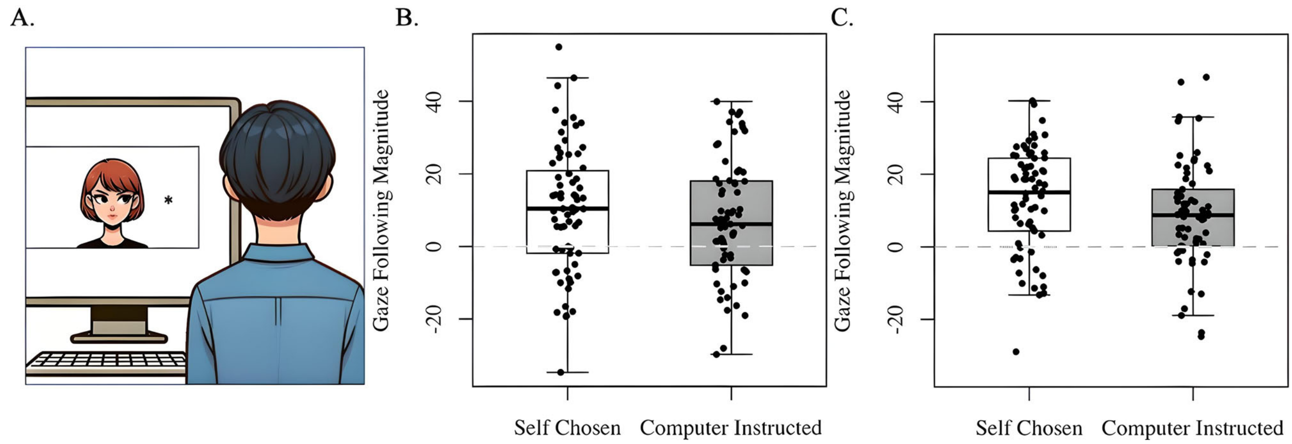

Fig. 2 | Experiments 2 and 3 design and results. A Example cuing task response display. Observers saw the gazer looking straight ahead for 2000 ms. At T_0, a response target along with the remaining portion of the eye movement was shown and remained visible for 2000 ms or until a response was made. **B** Experiment 2 results. Box plot showing Median magnitude (solid horizontal line) of gaze following (Incongruent RT– Congruent RT) as a function of Gaze intentionality (Self-chosen gaze vs. Computer-instructed gaze, $N = 73$ participants). **C** Experiment 3 results. Box plot showing Median magnitude (solid horizontal line) of gaze following (Incongruent RT– Congruent RT) as a function of Gaze intentionality (Self-chosen gaze vs. Computer-instructed gaze, $N = 70$ participants). Boxes encompass data points between the 25th and 75th percentiles, with whiskers indicating the larger minimum value and the smaller maximum value. Points represent individual participant's data.

was obtained from all participants. All procedures were approved by the McGill University Research Ethics Board.

Apparatus and stimuli. Stimuli were video clips of two female volunteers (i.e., gazers) looking left and right (Fig. 1A). To make these clips, each gazer sat in front of a 21.5-in LCD monitor screen at an approximate distance of 60 cm while their face and torso were filmed using a Vitade 1080-pixel resolution webcam camera positioned on the top center of the screen. Prior to starting the recordings, the gazers were informed that they were going to look to the left and right. They were asked to look in a natural and direct manner, as they would in real life, but to follow the timing of the instructions on the screen, which was implemented to assure uniformity across looking sequences. Then they were presented with a timed sequence of trials. On each trial, the gazers saw either a directional arrow or a double-sided arrow (each measuring 3.34° of visual angle) at fixation. The directional arrow instructed the gazers to look to the left or right (via the instruction 'Right/Left'). The double-sided arrow instructed the gazers to choose where to look (via the instruction 'Choose'). The instruction display lasted for 4000 ms. Then, a new screen with a green center dot and two white peripheral dots (each measuring 3.82° of visual angle) positioned at an eccentricity of 5.72° from fixation and set against a gray background was shown. The gazers then looked at one of the two peripheral placeholder dots as per instruction and remained looking at that location for an additional 4000 ms.

A total of 24 videos were recorded. Four could not be included due to equipment malfunction. Thus, 20 videos for each gazer were used, with 10 clips showing self-chosen eye movements (five to each left and right direction) and 10 clips showing computer-instructed eye movements. All trial videos were cropped to include 2000 ms of direct gaze before the eye movement initiation and 1000 ms of averted gaze after the eye movement initiation.

The study was administered online via Testable (https://www.testable.org/). The experiment was launched on participants' personal computers. Within each display, the recordings were scaled to 1280 × 720 px and equated for pixel size using the UniConverter 14 software (https://www.wondershare.com/). The video was played in full screen at 90% of the screen size. All stimuli were rendered in color.

Gazers displaying the stimuli were recruited from the McGill community. Both gazers were women (Gazer 1: 19 years old, Asian ethnicity; Gazer 2: 20 years old, White ethnicity). They were informed and agreed via the consent form that their recordings would be used in subsequent experiments, shown to other participants, and included as examples of stimuli in publications. The gazers received monetary compensation.

Design. The study was a repeated measures design with *Gaze intentionality* (2: Self-chosen; Computer-instructed), *Gaze direction* (2: Left; Right), and *Gazer identity* (2; Gazer 1; Gazer 2). *Gaze intentionality* varied between self-chosen and computer-instructed eye movements, which manipulated the mental state of intentionality in gaze. A separate control experiment (presented in detail in Supplementary Note 1) verified the manipulation of mental state in this task and showed that self-chosen relative to computer-instructed eye movements were perceived as occurring faster, which dovetails with the characteristics of intentional hand reaches, as reported by Pesquita and colleagues[22]. *Gaze direction* varied the gazers' looking direction between left and right. *Gazer identity* varied the identity of the gazer. Gaze intentionality and Gaze direction trials were intermixed and presented equiprobably. Gazer identity was blocked and randomized.

Procedure. Each trial began showing the gazer looking straight ahead for 2000 ms. At T_0, or the last frame before the eyes started to move from straight to averted position, the video was paused, and the observers were instructed to indicate quickly and accurately which side the gazer would look next by pressing either the 'b' or 'h' key on the keyboard, with target location (left, right) and key response ('b','h') pairing counterbalanced between participants (Fig. 1B). The still image captured at T_0 remained visible on the screen until response was made or until 2000 ms had elapsed, at which point the remaining part of the video revealing the direction of the eye movement was shown for 1000 ms. T_0 was identified manually by marking the last time frame in each video clip in which the gazer was looking straight ahead, occurring right before the first time frame when their gaze began to shift.

Participants completed 400 trials divided across four testing blocks, with each block containing 25 repetitions of Gaze intentionality × Gaze direction conditions. Eight practice trials were run at the start. Example stimuli can be viewed at https://osf.io/tywfb/.

Analyses. Repeated measures Analyses of Variance (ANOVA) were used to analyze the data, as reported in "Results". Data distribution was assumed to be normal, but this was not formally tested. When Mauchly's test was significant, the Greenhouse-Geisser degrees of freedom are reported. All follow-up *t*-tests are two-tailed, paired, and Bonferroni corrected for multiple comparisons.

Experiment 2

Participants. Data from 73 new participants recruited from the McGill volunteer undergraduate student participant pool were analyzed (61 women, 10 men, 2 others; gender reported by participants, mean age = 20.41 years, SD = 1.76, 62% White, 22% Asian/Pacific Islander, 16% Other). The study was preregistered on February 3, 2023, at https://osf.io/mb547.

A total of 76 participants completed the study and received course credit. Data from three participants were removed from analyses based on the preregistered exclusion criteria. All participants reported native English fluency, no history of psychiatric or neurological conditions, and normal or corrected-to-normal vision. All procedures were approved by the McGill University Research Ethics Board.

Apparatus and stimuli. The study was administered online via Testable (https://www.testable.org/). The experiment was launched on participants' personal computers. Stimuli were the same clips of natural eye movements shown in the same size as in Experiment 1. The task differed. In Experiment 2, a cuing task was used, whereby on each trial, a response target appeared at T_0 on either the left or right side of the gazer's face and participants were instructed to localize it by pressing the 'b' or the 'h' key on the keyboard (target side and key assignment were counterbalanced across participants). Images of a black asterisk measuring 1.91° were inserted into the original videos of eye movements using the VN software (https://www.vlognow.me/). The targets were positioned at an eccentricity of 8.57° from the center of the screen and horizontally aligned with the gazers' eyes (Fig. 2A).

Design. The study was a repeated measures design, with *Gaze intentionality* (2: Self-chosen; Computer-instructed), *Gaze-target congruency* (2: Congruent; Incongruent), and *Gazer identity* (2: Gazer 1; Gazer 2). *Gaze intentionality* and *Gazer identity* variables remained as before. *Gaze-target congruency* manipulated the spatial match between gaze direction and target location. Congruent trials were those in which the response target occurred at the gazed-at location; Incongruent trials were those in which the response target occurred at the not gazed-at location.

Eighty recordings were created from the twenty available videos from Experiment 1. For each gazer, 20 videos showed gaze-target spatially congruent conditions, and 20 videos showed gaze-target spatially incongruent conditions. Ten videos displayed left gaze congruent and incongruent targets, and ten videos displayed right gaze congruent and incongruent targets.

There was a total of 320 test trials, divided over four testing blocks. Each block contained 20 repetitions of each of the four Gaze intentionality (Self-chosen; Computer-instructed) × Cue-target spatial congruency (Congruent; Incongruent) conditions, which were intermixed and presented equiprobably. Gazer identity was blocked, such that the first and third blocks showed Gazer 1, while the second and fourth blocks showed Gazer 2, with the order of presentation counterbalanced. Sixteen practice trials were run at the start. Example stimuli can be viewed at https://osf.io/vyqmz/.

Procedure. Trials began with the gazer looking straight ahead for 2000 ms. At the first time frame after T_0 or the first frame of the eye movement initiation, the response target was presented on either the left or right side of the face and the video continued for 2000 ms revealing the eye movement. Thus, there was no pause in the video before participants responded. Trials timed out on response or after 2000 ms had elapsed.

Experiment 3

Participants. Data from additional new 70 undergraduate students recruited from the McGill volunteer undergraduate student participant pool (received course credit) and from Prolific Academic (https://www.prolific.com/; received $7.31 USD/hour) were analyzed (46 women, 23 men, 1 other; gender reported by participants, mean age = 25.00 years, SD = 5.31, 70% White, 23% Asian/Pacific Islander, 7% Other). The study was preregistered on February 3, 2023, at https://osf.io/mb547. Data from six participants were removed from analyses based on the preregistered exclusion criteria. All participants reported native English fluency, no history of psychiatric or neurological conditions, and normal or corrected-to-normal vision. All procedures were approved by the McGill University Research Ethics Board.

Apparatus, stimuli, and design

The study was administered online via Testable (https://www.testable.org/). All task stimuli and parameters were kept identical to Experiment 2, except that the response target appeared at one of the four different cue-target onset times with equal probability, i.e., simultaneously with the initiation of an eye movement (0 ms) as in Experiment 2, 100 ms after the initiation of an eye movement (100 ms), 300 ms after the initiation of an eye movement (300 ms), or 700 ms after the initiation of an eye movement (700 ms). Thus, in addition to *Gaze intentionality* (2: Self-Chosen; Computer-Instructed), *Cue-target congruency* (2: Congruent; Incongruent), and *Gazer identity* (2: Gazer 1; Gazer 2), Experiment 3 also manipulated *Cue-target onset time* (4: 0 ms; 100 ms; 300 ms; 700 ms).

For each Gazer identity, the same forty videos from Experiment 2 were used to include each of the four cue-target onset time, with twenty videos showing cue-target congruent conditions and twenty videos showing cue-target incongruent conditions (ten for each left and right side).

A total of 640 test trials were divided across four testing blocks. Each block contained 10 repetitions of each of the Cue-target onset time × Gaze intentionality × Cue-target spatial congruency conditions, which were intermixed and presented equiprobably. Gazer identity was blocked, such that the first and third blocks showed Gazer 1, while the second and fourth blocks showed Gazer 2, with the order of presentation counterbalanced. Sixteen practice trials were run at the start.

Procedure. Each trial began with the gazer looking straight ahead for 2000 ms. Then, at $T_{0,}$ they initiated the eye movement. Response target appeared following T_0 at 0 ms, 100 ms, 300 ms or 700 ms on either the left or right side of the face as the video resumed to reveal the directional eye movement. The display containing the cue and the target remained visible on the screen for 2000 ms or until a response was made.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Results

Experiment 1

Response anticipations and timeouts accounted for 14.89% of trials and were removed from further analyses. There were no statistically significant differences in trial attritions due to anticipations and timeouts as indicated by a repeated measures ANOVA that compared the attrition rates across experimental conditions (Self-chosen Right, Self-chosen Left, Computer-instructed Right, Computer-instructed Left; $F(3, 240) = 1.375$, $p = 0.251$, $\eta p^2 = 0.014$, 95% CI [−0.018, 0.065]).

Overall response accuracy was 44.46%, ($t(80) = -7.405$, $p < 0.01$, $d = -0.823$, 95% CI [−1.073, −0.569]). Accuracy for self-chosen and computer-instructed conditions was examined using a repeated measures ANOVA with Gaze intentionality (2: Self-chosen; Computer-instructed) and Gaze direction (2: Left; Right) included as variables, which revealed no significant main effects (Gaze intentionality $F(1,80) = 1.738$, $p = 0.191$, $\eta p^2 = 0.021$, 95% CI [−0.024, 0.01]; Gaze direction, $F(1,80) = 0.712$, $p = 0.401$, $\eta p^2 = 0.009$, 95% CI [−0.012, 0.057]) or interactions ($F(1,80) = 0.119$, $p = 0.731$, $\eta p^2 = 0.001$, 95% CI [−0.027, 0.017]).

Next, we used a repeated measures ANOVA with Gaze intentionality and Gaze direction to examine the mean correct Response Time (RT). As illustrated in Fig. 1C, and supporting our hypothesis, a reliable main effect of Gaze intentionality, $F(1,80) = 8.581$, $p = 0.004$, $MS = 33387.834$, $\eta p^2 = 0.097$, 95% CI [6.510, 34.095] indicated that self-chosen gaze trials were responded to faster than computer-instructed gaze trials. The main effect of Gaze direction, $F(1,80) = 4.166$, $p = 0.045$, $MS = 14932.570$, $\eta p^2 = 0.049$, 95% CI [0.340, 26.816] was also significant, showing that gaze shifts to the left were responded to faster than gaze shifts to the right. A two-way interaction between Gaze intentionality and Gaze direction, $F(1,80) = 7.617$, $p = 0.007$, $MS = 21958.160$, $\eta p^2 = 0.087$, 95% CI [11.93, 48.155], showed that participants responded faster to right gaze than to left gaze for the computer-instructed eye movements, $t(80) = 3.301$, $p = 0.001$, $d = -0.367$, 95% CI [−0.591, −0.141]. The difference between responses to right gaze and left gaze for self-chosen eye movements was not significant, $t(80) = 0.329$, $p = 0.743$, $d = 0.037$, 95% CI [−0.181, 0.254]. We also examined these data as a function of gazer identity and found no significant differences in these key effects (as presented in Supplementary Note 2).

Thus, Experiment 1 found that participants reported the direction of an upcoming self-chosen gaze faster than the direction of an upcoming computer-instructed gaze. This result held even though we analyzed all responses (correct and incorrect; Supplementary Note 2, Broad Response Analysis) to support the general idea that humans are sensitive to intentionality information in eye gaze. Specifically, the overall faster response times for self-chosen trials and broad response facilitation (along with a result showing no significant evidence for a similar difference in response accuracy) suggests an operation of an implicit mechanism responsible for a quick evaluation of mental state information in gaze as opposed to an operation of an explicit evaluation system, which is often associated with identification in accuracy responses[23]. Overall, then, and similarly to Pesquita et al.[22], our results show that intentional motion by the human eyes helps to communicate gazers' mental states even before the physical movement of the eye occurs.

In Experiments 2 and 3, we examined if such intentionality information in gaze also affected target-related gaze following responses.

Experiment 2

Response accuracy was 97.13%. There were no statistically significant differences in trial attritions due to anticipations and timeouts as indicated by a repeated measures ANOVA that compared the attrition rates across experimental conditions (Self-chosen Congruent, Self-chosen Incongruent, Computer-instructed Congruent, Computer-instructed Incongruent; $F(3, 216) = 0.247$, $p = 0.863$, $\eta p^2 = 0.007$, 95% CI [−0.011, 0.019]). Accuracy was examined using a repeated measures ANOVA with Gaze intentionality (2: Self-chosen; Computer-instructed) and Cue-target congruency (2: Congruent; Incongruent) included as variables, and revealed no statistically significant effects or interactions (Gaze intentionality, $F(1,72) = 1.074$, $p = 0.303$, $\eta p^2 = 0.015$, 95% CI [−0.007, 0.002]; Gaze-target congruency, $F(1, 72) = 1.470$, $p = 0.229$, $\eta p^2 = 0.020$, 95% CI [−0.002, 0.009]; Gaze intentionality × Cue-target congruency, $F(1, 72) = 0.162$, $p = 0.688$, $\eta p^2 = 0.002$, 95% CI [−0.007, 0.004]).

The same repeated measures ANOVA with Gaze intentionality and Gaze-target congruency examined the mean correct RTs. The results, illustrated in Fig. 2B, indicated a significant main effect of Gaze-target congruency, $F(1,72) = 17.764$, $p < 0.001$, $MS = 5750.144$, $\eta p^2 = 0.198$, 95% CI [4.677, 13.073] demonstrating the classic gaze following effect, e.g. ref.[13], with gazed-at (congruent) targets responded to faster relative to not gazed-at (incongruent) targets. There was also a main effect of Gaze intentionality, $F(1,72) = 6.527$, $p = 0.013$, $MS = 2182.945$, $\eta p^2 = 0.083$, 95% CI [1.202, 9.735], with self-chosen gaze responded overall slower than computer-instructed gaze. We addressed this result in an additional exploratory analysis that examined the influence of Gazer identity, which is presented in Supplementary Note 3. As detailed there, this analysis showed that the response speed difference between self-chosen and computer-instructed gaze was driven by differences in how the two gazers communicated mental state information. Specifically, the analysis indicated a significant interaction between Gazer identity and Gaze intentionality, revealing slower responses for Gazer 1 when her gaze was self-chosen compared to computer-instructed relative to faster responses for Gazer 2 when her gaze was self-chosen compared to computer-instructed. Critically, we found no evidence that the Gaze-target congruency, or the gaze following effect, interacted with Gaze intentionality ($F(1,72) = 0.796$, $p = 0.375$, $MS = 175.198$, $\eta p^2 = 0.011$, 95% CI [−1.143, 8.981]) or Gazer identity ($F(1, 72) = 1.167$, $p = 0.284$, $MS = 681.582$, $\eta p^2 = 0.016$, 95% CI [−13.675, 7.592]) and no statistically significant three-way interaction between Gaze identity, Gaze intentionality, and Gaze-target congruency, $F(1, 72) = 0.293$, $p = 0.590$, $MS = 199.968$, $\eta p^2 = 0.004$, 95% CI [−7.032, 17.923]. Thus, we found no evidence that gaze following response changed with variations in mental state communication from different gazers.

In summary, Experiment 2 showed a reliable gaze-following effect, with overall faster responses for gazed-at relative to non-gazed-at targets. However, no interactions between gaze following and gaze intentionality were statistically significant. Experiment 3 examined whether the timing between the presentation of the gaze cue and the response target influenced this result.

Experiment 3

Response accuracy was 96.54%. There were no statistically significant differences in trial attritions due to anticipations and timeouts as indicated by a repeated measures ANOVA that compared the attrition rates across experimental conditions collapsed across Cue-target onset time (Self-chosen Congruent, Self-chosen Incongruent, Computer-instructed Congruent, Computer-instructed Incongruent; $F(3, 207) = 0.355$, $p = 0.785$, $\eta p^2 = 0.009$, 95% CI [−0.005, 0.019]). Accuracy was examined using a repeated measures ANOVA with Gaze intentionality (2: Self-chosen; Computer-instructed) and Cue-target congruency (2: Congruent; Incongruent), and Cue-target onset time (4: 0, 100, 300, 700 ms). A main effect of Cue-target onset time, $F(1.850, 129.491) = 5.847$, $p = 0.005$, $MS = 0.023$, $\eta p^2 = 0.077$, 95% CI [−0.027, 0.000], indicated that participants responded more accurately to targets at the shortest time of 0 ms than at the longest time of 700 ms, and more accurately at the 300 ms time than the 700 ms time. No other effect was statistically significant (Gaze Intentionality: $F(1, 69) = 0.439$, $p = 0.510$, $\eta p^2 = 0.006$, 95% CI [−0.005, 0.002]; Cue-target congruency: $F(1, 69) = 0.311$, $p = 0.579$, $\eta p^2 = 0.004$, 95% CI [−0.005, 0.009]; Cue-target onset time × Gaze Intentionality: $F(2.464, 172.457) = 0.563$, $p = 0.606$, $\eta p^2 = 0.008$, 95% CI [−0.006, 0.011]; Cue-target onset time × Cue-target congruency: $F(2.693, 188.485) = 0.426$, $p = 0.713$, $\eta p^2 = 0.006$, 95% CI [−0.007, 0.01]; Gaze Intentionality × Cue-target congruency: $F(1, 69) = 2.188$, $p = 0.144$, $\eta p^2 = 0.03$, 95% CI [−0.009, 0.002]; Cue-target onset time × Gaze Intentionality × Cue-target congruency: $F(2.780, 194.622) = 0.968$, $p = 0.404$, $\eta p^2 = 0.014$, 95% CI [−0.007, 0.016]).

Mean correct RTs were examined using the same Gaze intentionality, Cue-target congruency, and Cue-target onset time repeated measures ANOVA. Figure 2C plots the magnitude of the gaze-following effect (Incongruent RT – Congruent RT) as a function of Gaze intentionality. Replicating Experiment 2, the analysis indicated a reliable main effect of Cue-target congruency, $F(1,69) = 51.355$, $p < 0.001$, $MS = 30846.442$, $\eta p^2 = 0.427$, 95% CI [7.574, 13.418], with overall faster responses for gazed-at or congruent relative to not gazed-at or incongruent targets. There was also a reliable main effect of Cue-target onset time, $F(2.012, 138.801) = 158.230$, $p < 0.001$, $MS = 208581.411$, $\eta p^2 = 0.696$, 95% CI [9.536, 20.426], with overall faster responses for targets occurring at longer cue-target intervals i.e., the foreperiod effect[24]. Gaze following displayed a time course of activity with facilitation at 100 and 300 ms, as supported by an interaction between Cue-target onset time and Cue-target congruency, $F(2.691, 185.661) = 3.966$, $p = 0.012$, $MS = 2707.741$, $\eta p^2 = 0.054$, 95% CI [10.68, 27.332]. Finally, a reliable main effect of Gaze intentionality, $F(1,69) = 31.817$, $p < 0.001$, $MS = 8922.552$, $\eta p^2 = 0.316$, 95% CI [3.649, 7.642] indicated that participants were significantly faster to respond to targets when the gaze shift was self-chosen relative to when it was computer-instructed. This main effect was qualified by a reliable Cue-target onset time × Gaze intentionality interaction, $F(3, 207) = 7.704$, $p < 0.001$, $MS =$

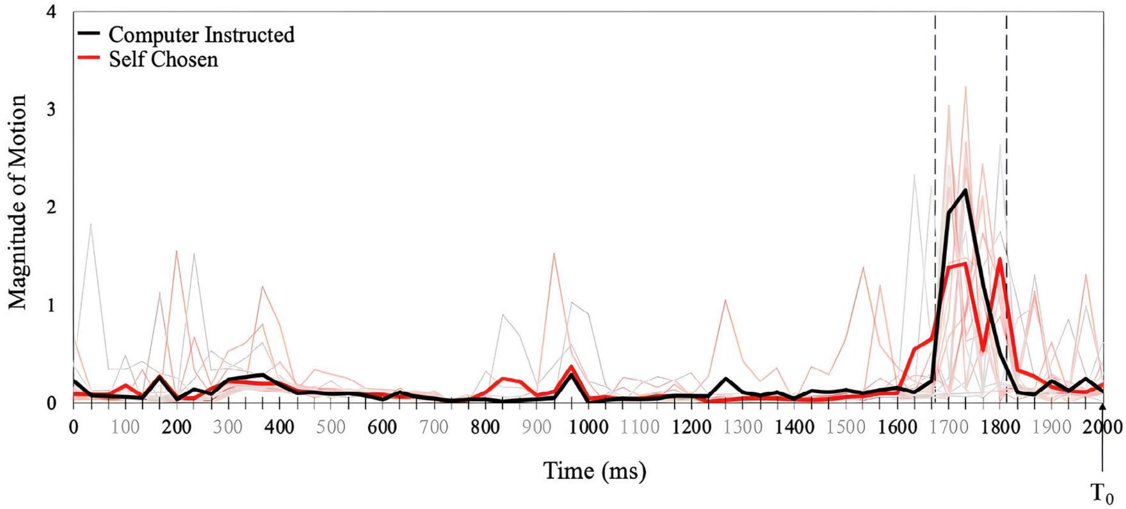

Fig. 3 | Motion within eye region during gaze shifts. The magnitude of motion in the eye region for self-chosen and computer-instructed gaze for 2000 ms prior to the eye movement initiation at T_0. Faded lines indicate motion values for each eye movement sequence. Solid lines indicate grand averages for self-chosen (red) and computer-instructed (black) conditions. Vertical dotted lines indicate the temporal time window at which the motion values were compared ($N = 120$ measurements).

3765.440, $\eta p^2 = 0.100$, 95% CI [15.216, 31.626], which indicated that significantly faster responses for self-chosen relative to computer-instructed trials occurred at cue-target onset times of 100, 300, and 700 ms. Supplemental Note 4 presents additional exploratory analysis which examined the influence of Gazer identity on this result (Experiment 3, Analyses of Gazer identity) and suggests that when observers are given more time to process gaze cue, i.e., when the cue-target onset is longer than 0 ms, they are better able to perceive the mental state information despite individual variation in the effectiveness of gaze communication from different gazers. No other effects were statistically significant (Gaze intentionality × Cue-target congruency: $F(1,69) = 1.713$, $p = 0.195$, $MS = 808.763$, $\eta p^2 = 0.024$, 95% CI [−0.390, 7.501]; Cue-target onset time × Gaze intentionality × Cue-target congruency: $F(2.718, 187.569) = 1.180$, $p = 0.317$, $MS = 555.761$, $\eta p^2 = 0.017$, 95% CI [−20.343, 1.53]).

In sum, Experiment 3 results replicated Experiment 2 results showing a reliable gaze-following effect, with faster responses for gazed-at relative to non-gazed-at targets. Experiment 3 also revealed that the timing of the presentation between the cue and the target mattered. Specifically, gaze following was reliable at 100 and 300 ms post cue, while faster responses to self-chosen gaze cues emerged at 100, 300, and 700 ms. For 0 ms cue-target onset time, responses to self-chosen gaze were slower than for computer-instructed gaze, replicating Experiment 2 results. This suggests that the processes of gaze following and mental state perception may operate on different time scales and in parallel. We return to this idea in "Discussion".

Importantly, and like Experiment 1, both Experiment 2 and Experiment 3 indicated behavioral sensitivity to intentionality information in gaze with response time facilitated by intentional gaze shifts. While responses varied somewhat with gazer identity, as would be expected based on individual differences in the ability to convey mental state information, as also reported by Pesquita et al.[22], the results consistently demonstrated behavioral sensitivity to intentionality information contained in gaze with no statistically significant influences on the gaze following effect.

Exploratory motion analysis

What is a possible mechanism by which mental states may be communicated by eye gaze? Recent research suggests biological motion as a potentially important signal of internal mental states, e.g., ref. 25, with kinematic movements affected by social context[26,27] and higher mirror neuron system activity during observations of socially intended movements relative to ones performed individually[28,29]. To probe into this possibility, we conducted an exploratory analysis that examined the amount of motion in the video clip available within the eye region of the gazers as a function of gaze intentionality. If eye motion information in self-chosen gaze differed from eye motion information in computer-instructed gaze, there should be differences in motion properties in the video clip between these two conditions. We used Optical Flow Analysis[30], which is explained in detail in Supplementary Note 5, to examine the amount of the overall motion signal in the region of interest spanning the eye region from both gazers across the 2000 ms before the eye movement initiation (i.e., T_0). Figure 3 depicts the magnitude of motion for all eye movement sequences for both gazer identities as well as the grand averages for self-chosen (depicted in red) and computer-instructed gaze (depicted in black). We identified a temporal window of interest by finding the video frame that contained the peak motion value and including the data from ± 1 frame around this peak. The average values of motion for self-chosen and computer-generated conditions at this time window were extracted and compared using a paired, two-tailed *t*-test. As illustrated in Fig. 3, self-chosen gaze ($M = 1.24$, $SD = 0.14$) was characterized by more overall motion within the eye region than computer-instructed gaze ($M = 0.72$, $SD = 0.19$), $t(2) = 6.882$, $p = 0.020$, $d = 3.973$, 95% CI [0.365, 7.769]. Importantly, and as can be observed in example stimuli, little perceptually discernible movement could be detected in the videos. Thus, very subtle motion information within the eye region appears to carry important signals to human mental state communication.

Discussion

In three experiments, here we examined the perception of mental states from human gaze and the influence of this information on observer behavior. Observers viewed videos of human gazers making natural eye movements. Gazers either looked in a direction they chose or in a direction they were instructed to look. In Experiment 1, we asked naïve observers to view eye movement sequences and to indicate an upcoming location of the gazers' eye movement before the eye movement was initialized. Self-chosen gaze was responded to faster than computer-instructed gaze. Response time differences to self- and computer-instructed gaze were replicated in Experiments 2 and 3, where we additionally tested if the perceived mental state of intentionality modulated target-related gaze following responses. We found no evidence for such modulation. Taken together, these data support the notion that humans are sensitive to mental state information in gaze.

Social prediction hypothesis maintains that compared to directed actions, chosen actions are more natural and follow more predictably from the current mental state of an agent[31]. This implies that the decision of the gazer may be communicated to the observer before the action of looking occurs. In our studies, the broad response facilitation was evident in the speed of responses in Experiment 1 even before the eye movement initiation, suggesting that gazers' decision to observers is communicated quickly, implicitly, and before the eye movement physically occurs. The results from Experiments 2 and 3 also suggest that implicit mentalizing did not affect gaze following, which remained statistically not significantly different across self-chosen and computer-instructed trials, even after combining data across two Experiments. The results additionally indicated that there may be individual differences in the extent to which mental state information from different gazers is accessible to observers.

The present results may offer a resolution to a longstanding question regarding the nature of human gaze signals by showing that eye gaze communicates both mentalistic and directional information but that these two processes may not necessarily influence one another. Thus, mental state information and directional information from gaze may be processed in a different manner. There are at least two possibilities to consider. First, it is possible that mentalizing and directionality processes may involve different underlying mechanisms, such that mentalizing attribution occurs quickly and implicitly, while directionality computation may require more deliberate and explicit processes. This would be in line with the idea that mental state attribution drives an initial response to gaze even before the eye deviates from its central position, while more deliberate processes involving evaluation, interpretation, and attribution of the gaze cue's meaning drive subsequent target-related attention orienting responses[14,32,33]. Second, and following from this, such a parallel operation mechanism would be compatible with different time scales of influence found in the present study including faster and implicit processing based on gaze mentalistic information and slower and deliberate processing based on explicit gaze direction or content. Our results showing observers' rapid behavioral sensitivity to gazers' mental states in Experiment 1 and a prolonged time influence on target-related processes in Experiments 2 and 3 support this idea. These possibilities make several exciting predictions for future work examining the influence of mentalistic and directional aspects of gaze, whereby one could, for example, examine how variables that affect deliberate processes affect the two types of gaze information.

Finally, our data provide a possible mechanism by which mental states may be communicated between individuals via gaze. That is, our OFA model suggests that the differences in mental state intentionality (as instructed to the gazers) are reflected in subtle differences in eye motion and, in turn, modulate an observer's behavior. As such, this raises a possibility that subtle motion signals within the eye region may communicate complex interpersonal messages. Future work is needed to understand how this may be accomplished and what information may be communicated. For example, one could examine if subtle movement differences within the eye region and the associated mental state perception would remain the same if the computer-directed cues were presented via a different (e.g., audio) modality or if the instruction to respond to the timing rather than location of the upcoming gaze shift affects how mental states are perceived. Similarly, an additional question relates to the notion of whether and how editing out the critical part from the gazers' video would influence the intentionality perception from gaze. Finally, studies using more fine-grained information about gazers' eye movements, such as those in which eye movement characteristics (e.g., velocity, trajectory, speed) are captured and measured using a high-speed eye tracker are needed to more precisely understand the nature of the motion signal associated with mental state perception.

Limitations

It is worth noting, however, that in our study, we used stimuli from two gazers only, and thus more gazer variety is needed to understand the effects of individual effectiveness in social cue delivery. Further, although our study was controlled with respect to the gender of the gazer and the gender of observers, most of whom were women, it would be important to investigate how intentionality perception may be modulated by the gazer's gender and/or interactions with participant gender. Finally, while here we have exerted a high level of experimental control over stimuli and procedures, in real life, contextual conditions may change how mental state information is extracted from gazers. As a case in point, our work examining eye contact in natural situations during unconstrained dyadic interactions found that although direct eye-to-eye contact between communication partners occurred only on about 3% of the interaction time, this communicative value was significant in guiding individuals' future gaze following behaviors[34]. Thus, an examination of the role of more complex contextual factors in mental state perception from gaze is needed as well.

Conclusions

In sum, here we demonstrate that human gaze communicates mental states, likely via subtle yet sophisticated motion information within the eye region. Together these findings provide a perspective on human social signaling via gaze and show that mental state information and directionality of gaze may convey parallel information.

Data availability

The anonymized data are available as open data via the Open Science Framework data repository at https://osf.io/tywfb/ and https://osf.io/vyqmz/.

Code availability

All codes used for each experiment are available via the Open Science Framework data repository at https://osf.io/tywfb/ and https://osf.io/vyqmz/, as SPSS Syntax files.

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Author contributions
F.M. and J.R. designed the study. F.M. created stimuli, collected and analyzed the data, and wrote the initial manuscript draft. J.R. supervised all stages of the project, and both J.R. and S.M. contributed to manuscript writing and edits.

Competing interests
The authors declare no competing interests.

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