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Mental-state attribution drives rapid, reflexive gaze following

Christoph Teufel, Dean M. Alexis, Nicola S. Clayton, and Greg Davis
University of Cambridge, Cambridge, England

When presented with a face stimulus whose gaze is diverted, observers' attention shifts to locations fixated by the face. Such "gaze following" has been characterized by some previous studies as a consequence of sophisticated theory of mind processes, but by others (particularly those employing the "gaze-cuing" paradigm) as an involuntary response that is triggered directly and reflexively by the physical features of a face. To address this apparent contradiction, we modified the gaze-cuing paradigm using a deception procedure to convince observers that prerecorded videos of an experimenter making head turns and wearing mirrored goggles were a "live" video link to an adjacent room. In two experiments, reflexive gaze following was found when observers believed that the model was wearing transparent goggles and could see, but it was significantly reduced when they believed that the experimenter wore opaque goggles and could not see. These results indicate that the attribution of the mental state "seeing" to a face plays a role in controlling even reflexive gaze following.

Humans exhibit a robust and well-documented tendency to direct their eyes and attention toward locations fixated by others. This "gaze-following" response forms a key component of sociocognitive and linguistic development (Baldwin, 1995; Brooks & Meltzoff, 2005; Carpenter, Nagell, & Tomasello, 1998; Frith & Frith, 2007). It is subserved by large-scale, specialized neural networks in the human brain (Hietanen, Nummenmaa, Nyman, Parkkola, & Hämäläinen, 2006) and is found in a diverse range of animal species (Emery, 2000; Schloegl, Kotrschal, & Bugnyar, 2007; Tomasello, Call, & Hare, 1998), emphasizing both its key role in human interaction and its broad adaptive significance. Despite its obvious importance, however, there is still disagreement as to the nature of the cognitive and neural processes underpinning gaze following in humans.

Typically, research in cognitive development has adopted a naturalistic experimental design initially pioneered by Scaife and Bruner (1975), in which the orienting response of the child is elicited by the experimenter's eye movements or head turns in various settings (for reviews, see Flom, Lee, & Muir, 2007; Moore & Dunham, 1995). Studies of this type have often linked gaze following to the development of a theory of mind (ToM)—the ability to understand behavior in terms of its underlying mental states. In particular, several recent studies have concluded that infants 12 months or older follow the gaze direction of others because they want to see what the other person is seeing or attending to (e.g., Baldwin, 1995; Brooks & Meltzoff, 2005; Caron, Kiel, Dayton, & Butler, 2002; Chow, Poulin-Dubois, & Lewis, 2008; Meltzoff & Brooks, 2008; Moll & Tomasello, 2004; Woodward, 2003; for reviews, see Gomez, 2005, and Meltzoff & Brooks, 2007). In other words, gaze following results from the attribution of a perceptual or attentional mental state to the other person and requires voluntary control—an interpretation that is in line with our folk-psychological intuitions.

However, despite their intuitive appeal, mentalistic accounts of gaze following are challenged by results of a thus far largely unrelated line of research in adult cognitive psychology. Although an experimenter's head or eye movements—which are typically used in infant studies—undoubtedly constitute the most "natural" stimulus for gaze following and lend themselves readily to manipulation of mental-state attribution, these movements cannot be controlled adequately to permit the assessment of rapid components of gaze following. In an attempt to circumvent this limitation, many studies of human adults have employed the "gaze-cuing paradigm," an experimental procedure derived from Posner's (e.g., 1980) seminal studies of visual attention that can provide an objective performance measure even of rapid, covert attention shifts. These studies typically find, in contrast with those in the developmental literature, that rapid saccadic and attentional shifts underlying gaze following in adults are triggered largely reflexively by the presence of a gaze stimulus (for a review, see Frischen, Bayliss, & Tipper, 2007). In keeping with this reflex account, mental-state attribution either is explicitly dismissed as a process in controlling gaze following (see, e.g., Bayliss, di Pellegrino, & Tipper, 2004; Driver et al., 1999; Fernandez-Duque & Baird, 2005) or is not discussed (e.g., Friesen, Ristic, & Kingstone, 2004; Hietanen et al., 2006).

Typical stimuli used in the gaze-cuing paradigm are pictures of faces whose eyes are averted to the left or right (see, e.g., Bayliss, di Pellegrino, & Tipper, 2005; Driver

C. Teufel, crt35@cam.ac.uk

et al., 1999; Friesen & Kingstone, 1998) or of heads that are rotated to gaze either to the left or to the right (e.g., Hietanen, 2002; Langdon & Smith, 2005; Langton & Bruce, 1999). Immediately following the presentation of the gaze cue on the computer screen, one of two targets appears in a left or right peripheral position. There are thus two different trial types: On valid trials, the face on the screen gazes toward the location in which the target subsequently appears, whereas on invalid trials, the face gazes away from the target's subsequent location. The task for the observers is to report which target is present by pressing one of two response keys as quickly as possible. With a short temporal delay (stimulus onset asynchrony, or SOA) between the gaze cue and the target, observers identify targets more quickly when the gaze cue validly cues the target's location (i.e., the face gazes to the side at which the target subsequently appears) than when it invalidly cues the target's location (i.e., the face gazes to the side opposite from where the target subsequently appears). Similar results are found when stimulus detection or localization is used (e.g., Friesen & Kingstone, 1998). This performance benefit for validly cued relative to invalidly cued targets (the "gaze-cuing effect") reflects preferential allocation of the observer's attention to the side of the display toward which the gaze cue was oriented.

Gaze-cuing effects readily occur in response to static, two-dimensional pictures of faces, and they arise despite the fact that observers know that the direction of the face's gaze has no predictive value regarding the likely subsequent location of the target. More importantly, the attentional control of gaze cues persists even when targets are more likely to appear on the side opposite from where the face gazes (Downing, Dodds, & Bray, 2004; Driver et al., 1999; Friesen et al., 2004; Senju, Tojo, Dairoku, & Hasegawa, 2004). Under these conditions, voluntary control of attention and reflexive responses to cue stimuli are directly opposed. For example, in an experimental design employed by Driver et al., the target letter was four times as likely to appear in a location opposite from that cued by the face's gaze. These cue–target contingencies were repeatedly pointed out to the observers. In order to identify the target as quickly as possible, the observers were supposed to shift their attention to the side opposite from that cued by the face's gaze (i.e., to the predicted but noncued location). Intriguingly, even under these conditions, observers identified validly cued (but nonpredicted) target letters faster than invalidly cued (but predicted) targets on short SOAs, indicating that they were unable entirely to suppress their tendency to follow the gaze of the face.

Counterpredictive designs, such as the one just described, provide powerful evidence that gaze stimuli exert reflexive control over an observer's attention. Moreover, evidence suggests that the characteristics that are specific to the attentional shifts underlying gaze following can be uncovered only with such a design. The neural networks that mediate cuing by gaze stimuli differ somewhat from those that control cuing by other directional cues, such as arrows (Hietanen et al., 2006; Kingstone, Friesen, & Gazzaniga, 2000; Ristic, Friesen, & Kingstone, 2002; for a review, see Nummenmaa & Calder, 2009). Nonetheless, contrary to initial findings (see, e.g., Jonides, 1981), recent studies have demonstrated that nongaze cues, such as arrows, can induce shifts of attention that are difficult to distinguish from those elicited by gaze cues, arising even when the cue is nonpredictive as to a target's subsequent location—that is, when valid and invalid trials are equally likely (Downing et al., 2004; Eimer, 1997; Hommel, Pratt, Colzato, & Godijn, 2001; Pratt & Hommel, 2003; Tipples, 2002).

Indeed, only in counterpredictive designs, in which invalid trials are more likely to occur than valid trials, do substantial performance differences between gaze cues and arrow cues (Friesen et al., 2004; Senju et al., 2004) or tongue cues (Downing et al., 2004) emerge. In particular, there is evidence to suggest that, in contrast with gaze cues, cuing by arrows or tongue cues can easily be overridden in a counterpredictive design so that orienting occurs to the predicted (but noncued) location only (Downing et al., 2004; Friesen et al., 2004; Senju et al., 2004). Gaze cues are thus, to a certain extent, resistant to top-down knowledge of cue predictive value, whereas other directional cues, such as arrows, do not show this reflexivity in the strong sense of the word. More recent studies, however, indicate that this dissociation might not be as clear-cut as was previously thought (Kuhn & Kingstone, 2009; Tipples, 2008). In any case, counterpredictive designs are crucial for investigating the strongly reflexive characteristics of attention shifts (a point to which we will return later) and might be better suited as a diagnostic tool to uncover the specific control that gaze cues exert over attention.

Taken together, the previous literature supports the consensus view that rapid components of gaze following in adults can be considered reflexive, suggesting a direct effect of perceived gaze on attention without modulation by ToM. The apparent contradiction between this conclusion and the consensus that gaze following in children *is* modulated by ToM might simply reflect automatization of such highly practiced responses during development. Alternatively, however, adult gaze cuing might yet be susceptible to the same ToM influences as gaze following in children. Technically, neither the presence of gaze cuing in response to static pictures nor the reflexive nature of gaze cuing logically precludes a role for ToM processes in these phenomena. Observers' online momentary processing of faces may erroneously attribute the mental state "seeing" even to static face pictures, and such attribution may even be necessary for reflexive gaze cuing to be observed. Indeed, one could argue that humans are highly trained in everyday life to attribute mental states to even the simplest two-dimensional characters depicted in advertisements and cartoons. Thus, the dismissal of mental-state attribution as a factor in the control of gaze following in adults seems premature. Indeed, whereas a plethora of developmental studies have explicitly examined the role of mental-state attribution in gaze following, only one recent study has attempted to address this topic in adults (Nuku & Bekkering, 2008).

Nuku and Bekkering (2008) compared gaze-cuing effects in response to a static image of a face with open versus closed eyes (Experiment 1) or of a face wearing sunglasses versus a face whose eye region was blocked out by a broad, dark square (Experiment 2). Larger gaze-cuing effects were found in the former than in the latter conditions of both studies. This result partly parallels findings in infants, showing that 10- to 14-month-olds follow the head turns of an experimenter more often when the adult's eyes are open than when they are closed (Brooks & Meltzoff, 2002, 2005; Caron, Butler, & Brooks, 2002).

Importantly, however, several authors have pointed out that experimental designs such as the ones just described are not able to uncover ToM processes in gaze following (Caron, Butler, & Brooks, 2002; Moll & Tomasello, 2004). One problem is that stimulus properties and (potential) mental-state attribution are confounded, making it impossible to determine which of these two factors is responsible for the differential findings. With respect to the study by Nuku and Bekkering (2008), this means that it is not clear whether weaker gaze-cuing effects in the adult participants were elicited by a face with closed eyes than by a face with open eyes (or by a face whose eye region was blocked out by a dark square than by a face wearing sunglasses) because observers attributed different mental states to these faces, or whether differences in the visual properties of the stimuli were responsible for the smaller gaze-cuing effects (e.g., were mediated by differential allocation of attention to the different types of stimuli).

In addition to the methodological problems of the Nuku and Bekkering (2008) study, the gaze-cuing effects reported did not meet the criteria for demonstrating strong reflexivity; such a demonstration requires a counterpredictive cuing design, as described above. Thus, to date, there is no clear evidence for an interaction of mental-state attribution and strongly reflexive processes in the control of gaze following. Nonetheless, such evidence would be worth pursuing, since it would provide a key opportunity to integrate the disparate theoretical perspectives from cognitive development and adult cognitive psychology.

The stimulus confounds of the Nuku and Bekkering (2008) study in examining potential ToM influences on gaze following are not a specific fault of that study alone, but rather reflect the limitations inherent in the conventional gaze-cuing paradigm. Accordingly, to address these issues in the absence of such confounds, we were compelled to adopt an approach radically different from the one taken in previous studies—one in which ToM processes could be manipulated directly in a setting that approximated a natural interaction while retaining precise control over the stimulus's physical characteristics.

We adapted the conventional gaze-cuing paradigm, replacing the static face images from previous studies with prerecorded video sequences of a "model"—one of the experimenters—turning his head to the left or right. Shortly after the model's head turn, one of two target letters appeared on either side of the model's face, and observers had to identify the target. Furthermore, we successfully convinced observers that the videos showed live footage of the model sitting in an adjoining room connected to the screen by a "live" video link. Observers thus believed that they were interacting with a real person during the experiment—a manipulation that disambiguated the mentalistic nature of the face stimuli and ensured that the observers attributed current mental states to the model, just as they would do when viewing a person outside the laboratory.

To manipulate whether the observer attributed a "seeing" or a "nonseeing" mental state to the model, the model wore one of two pairs of goggles. The lenses of both pairs were highly mirrored and thus looked identical from the perspective of an onlooker. The observers believed, however, that one pair was transparent from the perspective of the wearer and that the model therefore could see ("seeing" condition), whereas the other pair was opaque and that the model could not see ("nonseeing" condition; see Heyes, 1998). Note that all of the observers saw exactly the same stimulus material, and the stimulus properties could not, therefore, explain differential findings for the conditions. The only difference between the seeing and the nonseeing conditions that varied overall across observers was the belief of whether or not the model was able to see. Through this unique design, the aim of the present study was to determine whether the rapid components of gaze following—even though they are reflexive—are governed by mental-state attribution.

EXPERIMENT 1

To gather initial evidence for a role of mental-state attribution in rapid gaze following, in Experiment 1, the model gazed equally often toward and away from the location in which the target subsequently appeared (i.e., the direction of the model's gaze was nonpredictive regarding the target's likely position). These cue–target contingencies were repeatedly pointed out to the observers before each block of trials, and they therefore had no explicit strategic interest in shifting their attention in the direction of the gaze cue. In order to investigate the time course of the gaze-cuing effect, we employed a short and a long SOA. The short SOA employed in our study was within a range that has been shown to elicit robust reflexive attentional shifts in previous gaze-cuing studies (e.g., Driver et al., 1999; Friesen & Kingstone, 1998; Friesen, Moore, & Kingstone, 2005; Ristic & Kingstone, 2005); the long SOA was within a range in which previous studies found less or even a lack of facilitation (e.g., Friesen & Kingstone, 1998; Langton & Bruce, 1999). We therefore reasoned that if the attribution of the mental state "seeing" mediates the reflexive components of gaze following, it should enhance gaze-cuing effects in the seeing relative to the nonseeing condition on the short SOA. This effect should vanish on the longer SOA.

Method

Observers. Thirty-two observers (25 female; mean age: 26 years) gave written consent, were paid £6 for participating, and were fully debriefed after the experiment. Eight additional observers were excluded from the analysis either because they did not believe that the videos were a live video link ($n = 4$) or because their reaction times (RTs) exceeded 2 *SD*s above the group mean ($n = 4$). Later reanalyses with all of the observers included showed no change in the pattern of findings. The study received ethical approval from the

Psychology Research Ethics Committee of the Faculty of Biology at the University of Cambridge.

Materials. Stimuli were presented using an Apple Mac Mini Computer running PsyScope-X software and a Sony Trinitron screen. To construct the four pairs of goggles used in the study, a layer of mirrored window film was applied to the outside of the lenses of tinted swimming goggles, rendering them highly reflective. A blue, curved frame was added to two pairs of these goggles, and a yellow, serrated frame was added to the other two pairs. Finally, the insides of the lenses of one blue- and of one yellow-framed pair of goggles were made completely opaque. The other pairs were untreated and thus transparent to the wearer. Due to the presence of the mirrored window film, however, the lenses of all of the goggles had identical external appearances. Half of the observers, chosen at random, were provided with the experience of wearing yellow-framed goggles that were transparent from the perspective of the wearer and a blue-framed pair that was opaque; this pattern was reversed for the remaining observers. Hence, one pair of goggles always signaled that the model could see, and the other pair signaled that the model could not see.

Stimuli. The gaze cues consisted of video sequences (each 4,400 msec) comprising a head-and-shoulders view of a male model (author D.M.A.) wearing a pair of mirrored goggles (Figure 1). The whole video image subtended 20º horizontally × 16.2º vertically of retinal angle (viewed from 75 cm). In each trial, the model looked straight ahead for 2,400 msec; then, he turned his head to gaze to the left or right (Figure 1). Observers had to assess gaze direction from head orientation because the model's eyes were not visible through the goggles. Either 400 msec (short SOA) or 900 msec (long SOA) after the cue onset, one of two targets—an uppercase "T" or "L"—was presented 8.39º to the left or the right of the screen's center, subtending 0.75º × 1.07º. The cue onset was defined as the first frame in which the head motion could be detected when viewed in a frame-by-frame manner. Given that the head turn lasted for about 320 msec, however, the SOA between the moment when the head was in its final position (which corresponds most nearly to the stimuli used in previous studies) and the appearance of the target was about 80 msec on short trials and about 580 msec on long trials. To prevent the onsets of the targets from cuing their own position, their luminance was 110 $\text{cd}\cdot\text{m}^{-2}$, similar to that of the white background 115 $\text{cd}\cdot\text{m}^{-2}$. The targets disappeared when the observer responded.

Note that, due to the dynamic nature of our stimuli, the way in which our SOAs were measured is not directly comparable to the procedure in previous gaze-cuing studies. These studies used static images as cues that suddenly change orientation—a setup in which the cue onset is clear-cut for the observer. However, in our present study, the cue onset was technically defined as the first video frame in which a movement was discernible when viewed in a frame-by-frame manner; importantly, when viewed in normal motion, it is unlikely that this technically defined onset of the head turn was as directly perceivable as the sudden changes of orientation in previous studies. Consequently, whereas technically our SOAs were 400 and 900 msec long, their effective length might have been considerably shorter (relative to the technical SOAs of previous studies). Given that most previous studies did not find robust gaze-cuing effects with SOAs shorter than 300 msec, we decided not to choose a short SOA of (technically) 300 msec; rather, we chose a delay that was (technically) longer but still in a range that has been shown to produce robust cuing in previous studies.

Before the video started on each trial, a signal "Cam B ready? –" was presented at the center of the screen, subsequently overwritten by "Cam B ready? – ready." A gaze-cue video and a target letter then followed, as was described above. Finally, the signal "Cam off" was shown in the center of the screen. Together, the signals at the end of one trial and the beginning of the next trial constituted the intertrial interval of 2,050 msec and served to maintain the illusion that the observer's room was connected by a camera link to an adjoining room in which the model was sitting.

The video sequence in each trial was unique. Most clips were highly similar, but in a few of them, the model moved in a specific way (cheek scratching, coughing, etc.) to enhance the impression that the stimuli showed a live video link. Any differences between individual videos, however, could not have affected our findings because the videos were entirely counterbalanced across seeing versus nonseeing conditions, and were randomly assigned to valid or invalid trials, as well as to a short or long SOA. Note that all of the observers viewed exactly the same stimuli. The only consistent difference between the seeing and the nonseeing conditions was the observers' beliefs about whether or not the model could see.

Deception. Prior to the start of the experiment, we convinced observers that the (prerecorded) video sequences that they were viewing were from a live video link to an adjoining room, encouraging observers to attribute current mental states to the gaze-cue

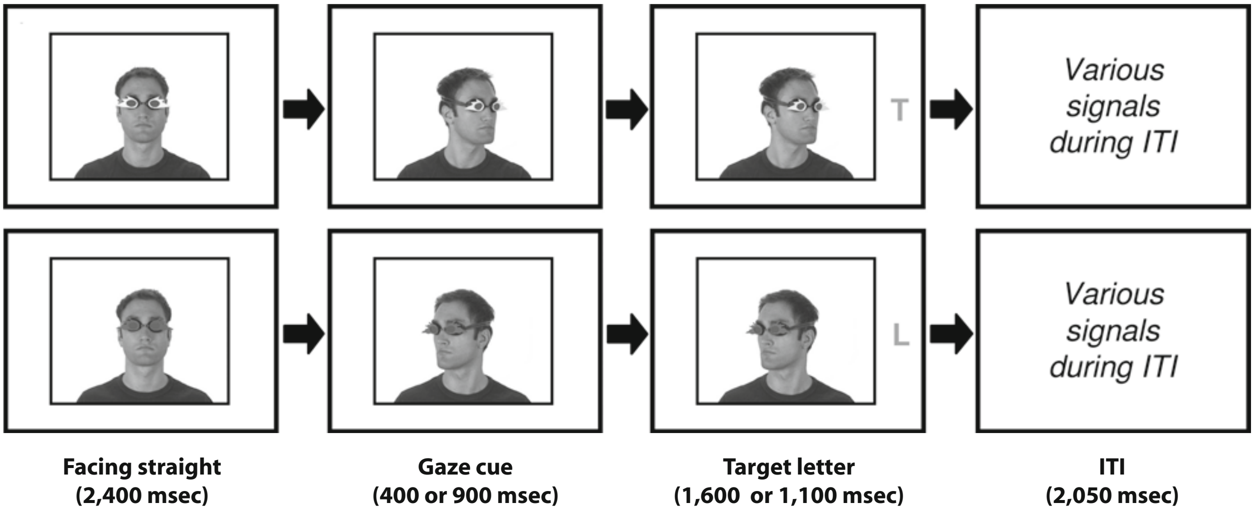

Figure 1. A schematic view of the experimental procedure. The top panel schematizes a trial in which the target's position is validly cued, and the lower panel schematizes a trial in which the target's position is invalidly cued. Half of the observers believed that the model could see through the yellow goggles, but not through the blue goggles; for the other half of observers, it was the other way around. During the intertrial interval (ITI), various signals were used in order to maintain the illusion that the video footage was an online video link to an adjoining room (see the Stimuli section for details).

stimuli. To maximize the success of this deception, observers were introduced in person to the model shown in the video sequences as a second participant, who was "set up" in an adjoining room. Once observers were seated in the testing room, the experimenter pointed out the webcam installed on top of the monitor and explained that the two rooms were connected in such a way that the observer would be able to see the other person during the experiment, and vice versa.

Observers tried on a blue and a yellow pair of goggles in order to gain first-person experience of the visual properties of the goggles. One pair was opaque, and the other was transparent (counterbalanced across observers). To convince observers that the videos were an online connection to the other room, we employed several manipulations to create the illusion of a contingency between the experimenter's behavior in the real world and the videos. When the experimenter pretended to switch on the cameras in both rooms and waved toward the camera above the video image of the model, the timing was such that the model showed a "thumbs-up" sign shortly after the experimenter's wave. This created the impression that the model could see the observer and the experimenter, and had thus responded to the experimenter's waving. The power of this illusion was evident in that most observers spontaneously waved back to the model in the video sequence. Observers included in the analysis reported that they were fully convinced that the videos showed another observer sitting in an adjoining room via a live video link. Additionally, most observers were noticeably surprised after the completion of the task when they were debriefed that they had watched prerecorded videos.

By employing such a deception, we attempted to approximate a real-life social interaction in order to trigger ToM processes similar to those in everyday life. In particular, when watching the model wear the pair of goggles that the observers had previously experienced as transparent, they should have attributed a "seeing" mental state to the other; when the model was wearing the second pair of goggles, they should have attributed a "nonseeing" mental state.

Procedure. The observers took part in two sessions of 96 trials each. In each trial, they saw a gaze-cue video and a target letter appear on the screen as was described above, and they had to identify the letter as quickly as possible. In one session, the model on the screen was wearing blue goggles, and in the other one, he was wearing yellow goggles. Each session was split up into two blocks consisting of 24 valid and 24 invalid trials, presented in a random sequence.

Written instructions indicated that observers should fixate the center of the screen and discriminate the appearing target letters as quickly and as accurately as possible by pressing the "H" key to indicate the letter "T," and by pressing the space bar to indicate the letter "L." The observers were (mis)informed that the person sitting in the adjoining room would participate in an auditory discrimination task in which he would turn his head to the left or the right. It was emphasized that "the direction the person turns to is completely irrelevant to the letter discrimination task, i.e., **it does not indicate where the letter will appear**" (bold text in the instructions). Additionally, observers were instructed to keep in mind whether or not the person on the screen was able to see, depending on which pair of goggles he was wearing.

Before the start of the first session, observers completed 20 practice trials consisting of a presentation of target letters without any central video cues. Practice trials were used to familiarize observers with indicating the target letters by pressing the corresponding buttons.

Design and Analysis. Since RT and accuracy (percentage correct minus percentage of errors) showed signs of differential tradeoffs across conditions, we employed the standard composite measure (RT/accuracy) first devised by Townsend and Ashby (1978, 1983) and subsequently labeled "inverse efficiency" (IE) by Murphy and Klein (1998). We used the IE data to calculate the cuing effects (performance on invalid trials minus performance on valid trials). For transparency's sake, however, we also report raw RTs, accuracy, and IE data separately. Following other studies of gaze cuing (see, e.g., Driver et al., 1999; Langton & Bruce, 1999), we determined prior to running the experiment that trials with RTs longer than 1,500 msec would be excluded from the analysis (2.5% of all trials).

We used a 2×2 within-subjects design: The first within-subjects factor was the condition, with the two levels, seeing or nonseeing. The sequence of conditions was counterbalanced across observers, as was the goggle color that indicated whether or not the model could see. The second factor was the SOA, which was either short (400 msec) or long (900 msec). Both SOAs were equally likely to occur. Initially, we conducted a mixed ANOVA including the within-subjects factors condition and SOA, as well as the between-subjects factors color (of the goggles) and order (of the conditions). There was no significant main effect of color or order, nor any significant interaction with these factors (the same is true for Experiment 2). For the sake of simplicity, we therefore report the results of the within-subjects analysis only. Post hoc analyses were conducted with paired-sample *t* tests and one-sample *t* tests. Note that all of the predictions for the pairwise comparisons between the seeing and the nonseeing conditions are direction specific, and we therefore used one-tailed tests for the paired-sample *t* tests throughout this study. All one-sample *t* tests were two tailed.

Results and Discussion

The cuing effects, in terms of IE, are plotted in Figure 2 (for RT and accuracy scores, see Table 1). As is clear from viewing the figure, observers showed larger cuing effects when they believed that the model could see than when they believed that the model could not see. A repeated measures ANOVA [condition (seeing vs. nonseeing) × SOA (short vs. long)] performed on the IE data confirmed this impression. There was a main effect of SOA [$F(1,31) = 49.5$, $p < .001$], but not of condition [$F(1,31) < 1$]. Importantly, however, there was also a significant SOA × condition interaction [$F(1,31) = 5.15$, $p < .05$].

Planned comparisons revealed the source of this interaction. At the short SOA, both seeing [one-sample *t* test, $t(31) = 6.7$, $p < .001$] and nonseeing [$t(31) = 6.4$, $p < .001$] conditions showed significant cuing effects; importantly, however, the gaze of the model cued observers' attention more strongly in the seeing than in the nonseeing condition [one-tailed paired-sample *t* test, $t(31) = 1.81$,

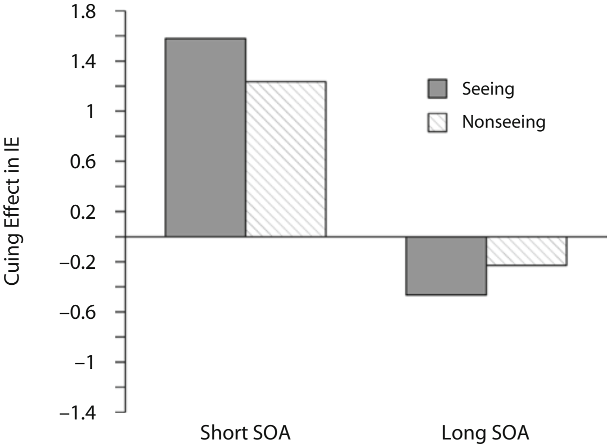

Figure 2. Mean cuing effects (performance on invalid trials minus performance on valid trials) in terms of inverse efficiency (IE) in the seeing and the nonseeing conditions on both stimulus onset asynchronies (SOAs) in Experiment 1.

Table 1
The Means and Standard Errors of the Means (*SEM*s) of the Reaction Times (RTs, in Milliseconds), the Mean Accuracy, and the Mean Inverse Efficiency (IE) in Experiment 1

	Short SOA				Long SOA			
	Seeing		Nonseeing		Seeing		Nonseeing	
	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid
RT	627.5	773.3	650.7	771.1	714.7	666.9	706.9	680.8
SEM	18.9	27.3	17.7	24.7	21.4	18.6	19.5	19.2
Accuracy (%)	98.6	97.1	98.0	97.9	98.4	98.1	98.8	98.1
IE	6.37	7.95	6.63	7.87	7.26	6.79	7.16	6.93

Note—Accuracy was calculated by subtracting the percentage of incorrect identifications of the target letter (errors) from 100%. All analyses that indicated significant results for the IE data (see the text) showed a significant effect or a clear trend ($p < .1$) for RT, accuracy, or both. Note that the group mean RT divided by the group mean accuracy does not yield group mean IE scores, because IE scores must be calculated individually for each participant.

$p < .05$], providing preliminary evidence that mental-state attribution might play a role in controlling the rapid components of gaze following.

At the long SOA, there was no significant difference between the seeing and the nonseeing condition [one-tailed paired-sample t test, $t(31) = -1.35$, n.s.]. Surprisingly, however, there was a significant reversed cuing effect in the seeing condition [one-sample t test, $t(31) = -3.74$, $p < .01$] and a trend in the same direction in the nonseeing condition [$t(31) = -1.8$, $p = .082$]. These effects may reflect inhibition of return (IOR). Technically, this term refers to a reduced speed in shifting attention to a location that has previously been attended to, and by doing so, IOR often biases attention to alternative locations (Frischen, Smilek, Eastwood, & Tipper, 2007; Klein, 2000; Posner & Cohen, 1984). We had not necessarily expected to find inhibitory effects in our experiment because previous studies have found IOR with gaze cues at much longer SOAs of 2,400 msec only (Frischen, Smilek, et al., 2007; Frischen & Tipper, 2004). IOR is, however, a complex and multifaceted phenomenon, and its early onset in the present study might have reflected the dynamic nature of our cue stimuli. Importantly, IOR is thought to be more strongly associated with reflexive than with voluntary shifts of attention; the finding that IOR was significant in the seeing but not in the nonseeing condition might therefore indicate that the attribution of a “seeing” mental state drives reflexive components of attention shifting more strongly than does the attribution of a “nonseeing” mental state. In any case, the absence of the same cuing effects at the long SOA as we found at the short SOA did preclude any explanation of our results at the short SOA in terms of task demands (the possibility that observers might attempt to generate the results that they believe the experimenter wants); such effects should arise at both SOAs.

A general finding of Experiment 1 demanding separate consideration is that, independent of condition, observers in our study appeared to respond more slowly than participants in most previous gaze-following studies (Table 1). The primary reason for this difference undoubtedly is that, in contrast with previous studies, we employed very low-contrast target letters. Given that such targets minimize cuing attention to themselves, they provide a purer measure of the gaze cue’s effects on attention, but they certainly require considerable time to be located and identified.

Overall, the results of Experiment 1 provided initial evidence that the attribution of a mental state to another person modulates rapid gaze following in adults. There is, however, one caveat to this conclusion: Observers might have allocated more attention to the model in the seeing than in the nonseeing condition, and this difference in attention allocation rather than a genuine interaction between mental-state attribution and the gaze-following system might be responsible for the results. Furthermore, recall from earlier that experimental designs such as that for Experiment 1, in which the cue is not predictive of the target’s location, can at best provide weak evidence of reflexive processing. The extent to which mental-state attribution influences the strongly *reflexive* components of rapid gaze following remains, therefore, unclear.

EXPERIMENT 2

In order to preclude an explanation of the results of Experiment 1 in terms of differential allocation of attention and to provide evidence of an interaction between mental-state attribution and the reflexive components of gaze following, we conducted an experiment with a counterpredictive design. In Experiment 2, we ensured that target letters were twice as likely to appear on the side opposite from where the model turned (i.e., the invalidly cued side) as on the same side to where the model turned (i.e., the validly cued side). On valid trials, the target thus appeared in a nonpredicted (but cued) location, whereas on invalid trials, the target appeared in a predicted (but noncued) location. Again, these contingencies between gaze cue and target were repeatedly pointed out to the observers. The observers’ optimal strategy, in terms of their voluntary control, was thus to shift their attention to the predicted location—that is, in the opposite direction from that cued by the model, yielding an expected reversed cuing effect: a performance benefit for invalidly cued targets (on the opposite side from the face’s gaze direction) relative to validly cued targets (on the same side as the face’s gaze direction). However, if observers’ reflexive processing tended to shift their attention in the same direction as the model’s head turn, this should mitigate or even abolish the reversed cuing effect. Accordingly, we predicted that if the attribution of the mental state "seeing" enhances reflexive components of gaze following, the reversed cuing effects should be smaller in the seeing condition than in the nonseeing condition. As we will discuss below, such a finding could not be explained by greater allocation of attention to the model in the seeing than in the nonseeing condition.

Method

Except for the fact that invalid trials were twice as likely to occur as valid trials (i.e., a counterpredictive design), the design, apparatus, and procedure of Experiment 2 were identical to those in Experiment 1. As before, each observer completed four blocks of 48 trials each (12 valid and 36 invalid trials). The instructions were identical to those in Experiment 1 in all respects, except that it was emphasized that the letter was "**twice as likely to appear on the side away from where the other person gazes**" (bold text in the instructions). As before, we excluded trials with RTs longer than 1,500 msec (0.7% of all trials).

Observers. Sixteen new observers (11 female; mean age: 26 years) who had not taken part in Experiment 1 participated. Additional observers who did not believe that the videos were a live video link ($n = 2$) or who had RTs that were 2 *SD*s above the group mean ($n = 1$) were excluded.

Results and Discussion

The mean gaze-cuing effects in terms of IE in Experiment 2 are plotted in Figure 3. As was expected, the reversed cuing effect was reduced in the seeing condition relative to in the nonseeing condition in both SOAs. A 2 × 2 ANOVA showed a main effect of condition [$F(1,15) = 12.62$, $p < .01$]; the other main effect and the interaction were not significant (for RT and accuracy scores, see Table 2). These results indicate that when observers assumed that the model could see, they were less able to suppress reflexive cuing of their attention in the direction of the model's gaze cues than they were when they assumed that the model could not see. Indeed, in both SOAs, the reversed cuing effects were significantly smaller in the seeing condition than in the nonseeing condition [one-tailed paired-sample *t* tests; short SOA, $t(15) = 2.53$, $p < .01$; long SOA, $t(15) = 1.87$, $p < .05$]. The reversed cuing effect was significant in the nonseeing condition in the long SOA [one-sample *t* test, $t(15) = -4.63$, $p < .001$]; it showed clear trends in the same direction in the short SOA in the nonseeing condition [$t(15) = -1.8$, $p = .09$] and in the long SOA in the seeing condition [$t(15) = -1.84$, $p = .08$].

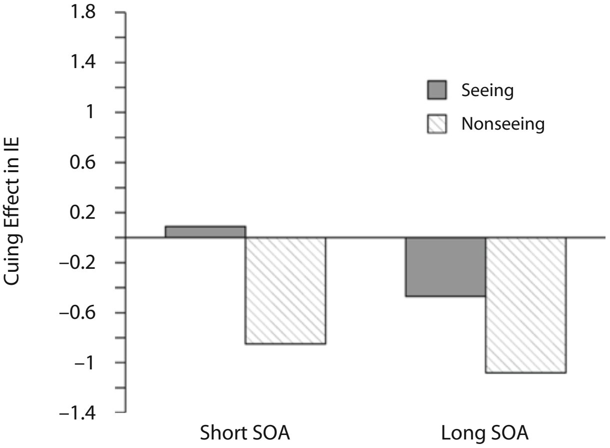

Figure 3. Mean cuing effects (performance on invalid trials minus performance on valid trials) in terms of inverse efficiency (IE) in the seeing and the nonseeing conditions on both stimulus onset asynchronies (SOAs) in Experiment 2.

In the seeing condition, on the short SOA, observers showed a numerical cuing effect in the direction of the model's gaze. This effect was, however, not statistically significant [one-sample *t* test, $t(15) = 0.3$, n.s.]—a finding that contrasts with previous gaze-following studies that employed a counterpredictive design (Driver et al., 1999; Senju et al., 2004). Our experimental setup, in which we attempted to emulate a real social interaction as closely as possible, differed in a couple of fundamental respects with previous studies that used relatively impoverished pictures of faces to cue attention. At present, it is not clear which of these factors was responsible for the differing finding. In two previous studies that employed a counterpredictive design with static pictures, however, it is unclear whether the gaze-cuing effect was significant (or merely numerical), because the relevant analyses were reported only for a small subset of the data (Downing et al., 2004; Friesen et al., 2004). In particular, Downing et al. (2004) never did directly compare cued (but nonpredicted) with predicted (but noncued) trials. Similarly, Friesen et al. (2004) conducted this analysis only for an SOA of 600 msec (but

Table 2
The Means and Standard Errors of the Means (*SEM*s) of the Reaction Times (RTs, in Milliseconds), the Mean Accuracy, and the Mean Inverse Efficiency (IE) for Experiment 2

	Short SOA				Long SOA			
	Seeing		Nonseeing		Seeing		Nonseeing	
	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid
RT	650.9	660.4	693.5	618.4	647.8	607.1	666.1	588.2
SEM	27.0	26.4	38.7	24.4	21.6	28.3	19.5	21.9
Accuracy (%)	94.5	94.1	92.6	93.6	95.3	96.1	93.7	96.9
IE	6.93	7.02	7.51	6.67	6.79	6.32	7.14	6.06

Note—Accuracy was calculated by subtracting the percentage of incorrect identifications of the target letter (errors) from 100%. All analyses that indicated significant results for the IE data (see the text) also showed significant results for the analogous analysis of the RT data. Again, note that the group mean RT divided by the group mean accuracy does not yield group mean IE scores, because IE scores must be calculated individually for each participant.

not the other SOAs employed in this study) and, similar to our study, found no significant difference between these trial types. It is therefore not clear whether our study falls outside the range of previous results, or whether the different findings can be considered part of the inherent variability of the gaze-cuing effect in counterpredictive designs. Logically, it remains possible that the absence of a significant cuing effect on the short SOA in the seeing condition might have been partly due to low statistical power. It is possible that with a larger sample size, we would have uncovered such an effect, although our present sample sizes compare well with those employed previously in this literature.

Importantly, our conclusion that observers were less able to suppress reflexive cuing of their attention by the model's gaze in the seeing relative to the nonseeing condition does not require there to be a significant cuing effect in the direction of the model's gaze in the seeing condition on the short SOA. Rather, the crucial finding to support this interpretation is that, in a direct comparison between the seeing and the nonseeing conditions, the ToM manipulation significantly reduced the reversed cuing effect (i.e., the cuing effect away from the model's gaze) when observers believed that the model could see, as compared with when they believed that the model could not see. However, this influence of ToM was not large enough to induce a significant cuing effect in the direction of the model's gaze at the short SOA in the seeing condition. The latter result leaves the findings of Experiment 2 open to an alternative explanation—namely, that observers oriented neither reflexively nor voluntarily in that condition because of generalized inhibition of attention shifting by the presence of a seeing model. This explanation would indeed account for the reduced cuing effects in the seeing condition of Experiment 2. However, it is inconsistent with the findings from Experiment 1, in which attention shifting was enhanced rather than inhibited in the seeing condition.

Taken together, the seeing condition (relative to the nonseeing condition) enhanced attention shifts toward the model's direction of gaze in Experiment 1 and reduced attention shifts away from the model's direction of gaze in Experiment 2. That is, the seeing condition in both experiments yielded a net bias (relative to the nonseeing condition) toward where the model was gazing in both experiments. Moreover, this net bias appears to have been reflexive in the sense that it arose even when it was contrary to the participant's strategic interests in Experiment 2, preventing them from searching the noncued side at which targets were most likely to appear. On this account, the absence of a cuing effect at the short SOA in the seeing condition of Experiment 2 reflects the simultaneous working of two components: a voluntary component that biased attention to shift toward the predicted (but noncued) location, and a reflexive component that directed attention toward the cued (but nonpredicted) location, mutually canceling one another. Such interplay and temporal overlap of voluntary and reflexive components have been convincingly demonstrated by Friesen et al. (2004).

It is important for us to note that the results of Experiment 2 could not be explained by greater allocation of attention to the model in the seeing than in the nonseeing condition. The observers were better able to use the direction of the model's head turn to shift their attention in the opposite direction, indicating that, if anything, they were attending more to the model in the nonseeing than in the seeing condition.

GENERAL DISCUSSION

In the present study, we adopted the gaze-cuing paradigm to measure rapid, reflexive shifts of attention in response to gaze cues, and we modified the task in such a way that ToM processes could be directly manipulated. The results indicate that mental-state attribution exerts an important influence even on the rapid, reflexive components of gaze following in adults. First, when observers believed that the person who provided the gaze cue could see, their gaze following was enhanced relative to when observers believed that the model could not see (Experiment 1). Furthermore, in Experiment 2, the observers had an explicit strategic interest in shifting their attention away from the direction of the gaze cue. Under these conditions, when observers believed that the model could not see, they were able to direct their attention voluntarily away from the model's gaze direction. However, when observers attributed the mental state "seeing" to the model, they were unable to voluntarily orient away from the face, suggesting a reflexive component that counteracted the voluntary process and that observers were not entirely able to suppress. Thus, it appears that the influence of reflexive processes controlling social attention is stronger when observers attribute a "seeing" mental state than when they attribute a "nonseeing" mental state.

This finding provides a means to integrate contrasting perspectives on gaze following in human cognitive development and adult cognitive psychology. Whereas the former approach has favored a mentalistic interpretation (Baldwin, 1995; Brooks & Meltzoff, 2005; Caron, Kiel, et al., 2002; Chow et al., 2008; Gomez, 2005; Meltzoff & Brooks, 2007, 2008; Moll & Tomasello, 2004; Woodward, 2003), the latter has typically characterized gaze following as a reflex and has often either dismissed or ignored any mediation by mental-state attribution (Bayliss et al., 2004; Driver et al., 1999; Fernandez-Duque & Baird, 2005; Friesen et al., 2004; Hietanen et al., 2006). However, the results of the present study suggest that, rather than being mutually exclusive alternatives, ToM and reflexive processes interact in the control of gaze following. In fact, attribution of the mental state "seeing" to a face stimulus increases the reflexivity of rapid gaze-following responses (relative to attribution of the mental state "nonseeing"). This was particularly evident in Experiment 2, in which we employed a counterpredictive design. Such a design provides powerful evidence for reflexive processes because it explicitly sets voluntary control of attention in opposition to the direct effects of the stimulus (Downing et al., 2004; Driver et al., 1999; Friesen et al., 2004; Senju et al., 2004).

It is not surprising that the specific differences between the seeing and the nonseeing conditions were most prominent in Experiment 2. Recall from earlier that in nonpredictive designs, even arrows produce cuing effects similar to those of gaze cues (Downing et al., 2004; Eimer, 1997; Hommel et al., 2001; Pratt & Hommel, 2003; Tipples, 2002). However, there is some evidence that counterpredictive designs uncover specific differences between these social and nonsocial cue types: Observers are able to shift their attention away from the direction of a counterpredictive arrow even on short SOAs, whereas they are not able to entirely suppress attending in the direction of a counterpredictive gaze cue (Downing et al., 2004; Driver et al., 1999; Friesen et al., 2004; Senju et al., 2004). It has therefore been argued that counterpredictive designs are better suited than nonpredictive designs to reveal the specific characteristics of rapid, reflexive gaze following. It is tempting to speculate that the gaze cues in the nonseeing condition of our present study are, to some extent, processed similarly to nonsocial arrow cues, and that ToM processes transform these gaze cues by top-down modulation into powerful social signals that exert strongly reflexive control over an observer's attention. We do not wish to claim, however, that mental-state attribution is the only factor that governs gaze following. The specific physical properties of a gaze cue are certainly of crucial importance. According to our view, another person's looking behavior can be represented on various different levels, two of which are its purely physical properties and its underlying mental states. These levels work together in governing gaze following, and our results suggest that the mentalistic representation drives the reflexive components of the behavior. We must emphasize, however, that the results of the present study support the conclusion that mental-state attribution drives reflexivity only for the rapid components of gaze following. The slow, overt gaze-following responses typically measured in studies on human cognitive development might not show this striking interaction.

As was mentioned before, the results of the present study differ in a couple of respects from those in previous gaze-following studies. Whereas we already separately scrutinized these differences at other points throughout the article, we would like to highlight a more general point here. Recently, several authors have begun to emphasize the importance of maximizing ecological validity (as well as maintaining full stimulus control) of laboratory-based tasks (Kingstone, Smilek, & Eastwood, 2008; Kingstone, Smilek, Ristic, Friesen, & Eastwood, 2003; Sebanz, Knoblich, & Humphreys, 2008). This approach might seem very familiar to developmental psychologists, who have concerned themselves intensively with the ecological validity of their tasks, but it is new to most researchers working with adults. The present study contributes to this project by examining how social signals operate to influence attention in a setting that at least approximates to a real-world interaction while retaining the full advantage of a laboratory-based task. Thus, the differences between our experiments and previous studies that employed relatively impoverished pictures of faces as stimuli were to be expected. These differences should, however, not be considered a weakness of either our design or those of previous studies. Rather, both types of studies are important and will, in the future, play complementary roles in shedding light on sociocognitive processes in humans. Whereas the use of pictures greatly improves the feasibility of experimentation and therefore lends itself to detailed analyses of lower level processes contributing to gaze cuing, our approach might help in the understanding of the high-level sociocognitive characteristics that influence social processing in everyday life.

The primary aim of our present study was explicitly to manipulate mental-state attributions that are crucial in real-world social interactions. However, we do not claim that observers might not attribute mental states to pictures of faces, as used in previous gaze-cuing studies. This might well be the case. Rather, we merely note that pictures of faces constitute highly ambiguous stimuli regarding mental attribution, because observers are certainly aware that pictures cannot "see" or "think." At present, we simply do not know to what extent they trigger the same ToM processes present in a real human being (but see Heider & Simmel [1944] for evidence suggesting that humans attribute [motivational] mental states to moving geometrical forms). For this reason, our deception procedure, which convinced observers that they were interacting with a real person, is of crucial importance to the conclusion that the attribution of mental states can modulate gaze cuing.

Although the gaze-cuing effect is considered to be highly reflexive, it is noteworthy that some previous studies have shown modulatory influences. For example, facial expressions of fear have been shown to enhance the gaze-cuing effect under certain circumstances (Mathews, Fox, Yiend, & Calder, 2003; Tipples, 2006), as have manipulations of the eye region of the face pictures used as cues (Nuku & Bekkering, 2008). Note, however, that the modulations shown in these studies are entirely different from the influence of mental-state attribution demonstrated in the present study, since they concerned themselves exclusively with the influence of changes in the stimulus properties. An exception is an elegant study by Ristic and Kingstone (2005), in which an ambiguous stimulus elicited gaze-cuing effects only when it was interpreted as a face with averted eyes rather than as a car. With respect to the control of stimulus properties, this study comes closest to our novel version of the gaze-cuing paradigm. In contrast with Ristic and Kingstone, however, we directly manipulated mental-state attribution rather than the interpretation of a face stimulus as a face.

At first glance, it might appear entirely unnecessary that gaze following should be governed by the interaction between ToM processes and reflexive responses. In the laboratory, there are typically one or two very distinct objects or locations that another individual might feasibly be looking at, so that even a cursory assessment of the other person's eye direction suffices to disambiguate which object/location has engaged his or her attention. However, this is not so for typical natural environments, which are replete with dozens of candidate objects that another individual might be attending to. Accordingly, sophisticated ToM processes might be required to determine which object the other person might be looking at. To illustrate, consider these examples. First, another person's facial expression will provide valuable clues as to his or her focus of attention. If the expression is fearful, it is likely that he or she is attending to a stimulus that poses a threat. Note that the stimuli that might be associated with a fear response would depend entirely upon the (unobservable) mental states of the individual whose face we are observing; hence, the modeling of his or her internal states is helpful to make efficient use of the information provided by the facial expressions. Second, taking the other's mental states into account might help to exclude some candidate objects or locations as the focus of another's visual attention in cases in which there are barriers between looker and object. Indeed, a purely reflexive control of gaze following might be disadvantageous in the more complex social situations that are typical of human interactions. Consider the situation in which another person is looking (physical properties level) but not attending (mental state level). Following the gaze of such an individual is of very little, if any, importance in social contexts. A system that suppresses following the gaze of such an individual or that enhances gaze following in response to another individual who is attending might guarantee the behavioral flexibility that is necessary for proper social functioning. In other words, such a system of various representational levels allows an observer to act on the deeper social dimension of another person's looking behavior.

In summary, we report in the present article that ToM processes strongly influence rapid, reflexive gaze-following responses in adult observers—a finding that accords with recent conclusions concerning perception of others' actions (Liepelt, von Cramon, & Brass, 2008). The finding that observers are unable to entirely suppress their gaze-following response when they believe that the model is able to see highlights a previously unsuspected and intriguing interaction between mental-state attribution and reflexive processes in the control of rapid attention shifts in response to gaze cues, providing a means to integrate disparate perspectives on gaze following from cognitive development and adult cognitive psychology. Furthermore, this interaction points to a more general involvement of high-level social processing in the moment-by-moment decisions about the objects in our environment that we prioritize for attention. The counterintuitive combination of two key features of this interaction—namely, its cognitive sophistication and its reflexive control of attention—may maximize the adaptive value of gaze following by ensuring that such core processes in social cognition are not entrusted to crude, stimulus-driven control or to the whims of voluntary, strategic processing.

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