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LETTER TO THE EDITOR

The Eyes Have It: Perception of Social Interaction Unfolds Through Pupil Dilation

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Dear Editor,

It is well-known that pupil size, albeit intrinsically sensitive to ambient luminance changes, can be modulated by many cognitive processes, especially those associated with physiological arousal [1]. Compatible with this view, when observers are watching or even anticipating reward stimuli that satisfy their needs (e.g., a monetary reward [2] or smoking-related pictures for smokers [3]), their pupils dilate due to a heightened state of arousal. On the other hand, according to social motivation theory, healthy human individuals are ingrained with social motivation to orient towards biosocial signals, to seek out pleasure in social interactions, and to maintain social affiliations [4]. Biosocial signals (e.g., face and biological motion) that drive social motivation, are therefore granted attentional priority [5] and have a rewarding function [6]. In line with previous findings that reward-related processing dilates pupils [2, 3], our innate preference for biosocial signals can be reflected by pupil size as well [5, 7]. In essence, such preference for biosocial signals ought to rely on communicative intentions heavily embedded in social interactions. Although social motivation theory proposes that people want and like to engage in social interactions [4], to our knowledge, no study has yet provided empirical evidence that our intrinsic preference for social interaction is simply manifested in pupil size.

Given that the everyday social interaction scenarios with which we are inundated consist of either an agent who sends an interactive invitation towards us (a second-person perspective) or pairs of people who are engaged in reciprocal communications (a third-person perspective), in the present study we systematically investigated the change of observers' pupil size while they viewed these two types of social interaction. We recruited 100 participants (18–28 years old), with 20 participants in each experiment (Experiment 1a: 10 males; Experiment 1b: 7 males; Experiment 2a: 8 males; Experiment 2b: 8 males; Experiment 3: 7 males). They gave informed written consent prior to the experiments, which were approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences, and conformed to the tenets of the Declaration of Helsinki.

First, we investigated whether viewing an agent with an interactive intention towards the observer (a second-person perspective) caused pupil dilation in Experiment 1. To reduce the potential influences of other confounding factors, we opted for point-light displays to simulate social interactions. These stimuli were action initiators who conveyed a communicative intention, selected from five pairs of two interactive actors (the "no", "get down", "come closer", "move over", and "stand up" displays

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from the Communicative Interaction Database [8]). For example, in the "come closer" display, we chose the person waving his hand to ask another person to come here. We then manipulated the body orientation of the chosen agent (Fig. S1), rendering it either oriented straight towards the observer (observer-oriented condition) or oriented 70° to the right/left of the observer (others-oriented condition).

Each trial began with a central fixation (0.2° × 0.2°) with a variable duration (800–1200 ms), followed by the point-light display (PLD) presented in the center of the screen for 3000 ms (Fig. 1A). The PLD (one agent) subtended 4.2° × 8.0°. To maintain participants' attention on the displays, a sudden luminance change of the PLD (31.45 cd/m^2) occurred in 20% of trials, and participants were required to accurately detect such changes by pressing a button after the PLD disappeared. The inter-trial interval was set to 3000 ms. There were 40 trials for each condition, presented with equal probability in a random order and divided into 4 blocks. Pupil diameters were recorded by an iView X Hi-Speed eye tracker system sampling at 500 Hz (SMI, Berlin, Germany). Only trials without luminance change of the PLDs were used for pupil analysis. The raw pupil size for each trial was first preprocessed to remove eye-blinks (either replaced by linear interpolation or with this trial discarded). Then, trials with pupil size deviating ±3 SDs from the mean were excluded from further analysis. Finally, the pupil size data were down-sampled to 20 Hz and baseline-corrected for each trial by subtracting the mean pupil size during the 200 ms pre-stimulus period. Consecutive paired-sample *t*-tests across all time-points after the stimulus onset were computed separately for each condition, and a cluster-based permutation analysis was applied to avoid potential problems associated with multiple comparisons [9]. In this analysis, the computed *t*-values neighboring in time that exceeded a threshold ($P < 0.05$) were defined as clusters, and then summed to produce a cluster mass. The cluster mass was compared with a null distribution, which was generated by 2000 random permutations of the pupil data from different conditions. If the cluster mass fell beyond 95% of the null distribution ($\alpha = 0.05$), it was deemed to be statistically significantly different.

The results of Experiment 1a revealed that participants' pupils were significantly dilated between 450 ms and 1300 ms in the observer-oriented *versus* the others-oriented condition (Fig. 1B). However, the pupil dilation effect disappeared when the agents were presented inverted in Experiment 1b (Fig. 1C), excluding the possibility that this effect was governed by any subtle luminance difference between PLDs of different orientations. As expected,

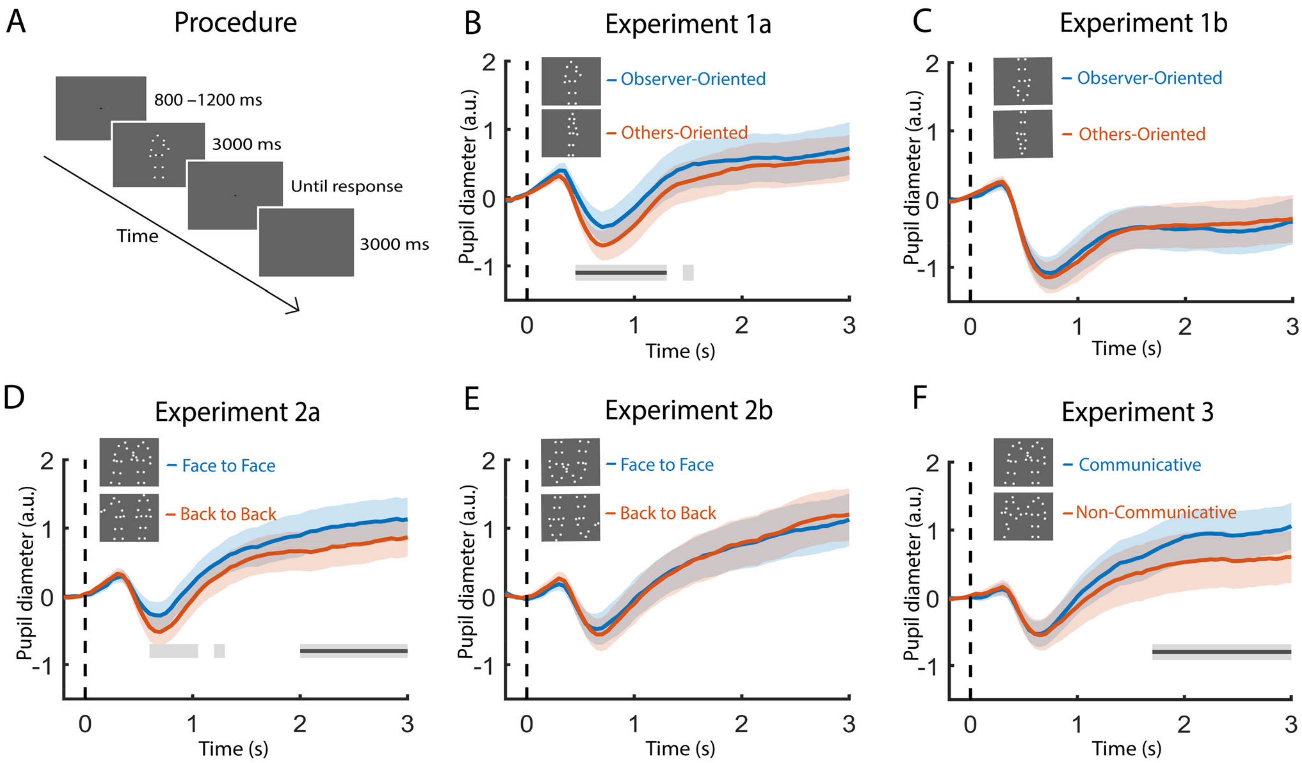

Fig. 1 **A** The experimental procedure. **B–F** Results from Experiments 1–3. Solid lines represent pupil diameter under different conditions as a function of time; shaded areas represent the SEM between participants; horizontal gray lines indicate periods during which there are statistically significant differences between conditions at P <0.05; and horizontal black lines indicate significant differences after cluster-based permutation correction. All the pupil data are in arbitrary units (a.u.).

viewing an agent conveying a communicative intention towards us causes pupil dilation. In reality, we are not only adept at detecting the communicative invitation directed towards us, but also highly attuned to others' social interactions from a passive view (a third-person perspective). Therefore, we further examined whether dyadic social interaction entities can induce pupil dilation as well in Experiment 2.

The procedure in Experiment 2 was identical to that in Experiment 1 except that the displays were replaced by dyadic agents. Stimuli were selected from the Communicative Interaction Database [8], consisting of five social interaction videos ("give me", "I am happy", "pick up", "stand up", and "get down") in which two agents engaged in mutual communicative interactions (e.g., in the "give me" display, A asks B for something; B takes it and gives it to A). To create non-interactive stimuli, the interactive dyads were re-assembled facing away from each other (back-to-back condition) instead of facing each other (face-to-face condition). As illustrated in Fig. 1D, participants' pupils showed significantly greater dilation during the face-to-face displays than during the back-to-back displays in the 2000–3000 ms range. By contrast, pupil size did not differ when the displays were presented upside-down in the control experiment (Experiment 2b, Fig. 1E). Experiment 2 thus provided the first empirical evidence that pupils dilate when participants view social interaction displays from a third-person perspective.

However, some may argue that it was the facing configuration of the dyads rather than the communicative intention that caused this effect. To test this, we applied a strict means of generating non-interactive dyads in Experiment 3, where the action initiators of the communicative dyads were replaced by another irrelevant actor to create non-communicative dyads [10]. The irrelevant actors were agents who performed individual actions (i.e., "crawl", "cycle", "jump", and "walk" from the Biological Motion Database [11]). By this means, all the agents faced each other in both the communicative and non-communicative displays (Fig. S1). Besides, a new intention judgment task was introduced, which required participants to explicitly judge whether the two agents were communicating with each other or acting independently. Since the low-level physical difference between the communicative and non-communicative displays did not affect pupil size in Experiments 1 and 2, no additional inverted counterparts were included in Experiment 3.

Similar to Experiment 2, there was significant pupil dilation in response to the communicative dyads from 1700 ms until the disappearance of the display compared to the non-communicative dyads (Fig. 1F). Critically, our data confirmed that it was the mutual communicative intention delivered by the facing dyads rather than their facing configuration that had caused the pupil dilation. Taken together, Experiments 2 and 3 consistently demonstrated that the perception of dyadic social interactive agents, similar to the perception of a facing interactive agent, causes pupil dilation.

Previous studies have demonstrated that pupil size is enlarged by biosocial signals relative to non-biosocial signals [5, 7]. In the present study, we extended these findings by demonstrating that pupils significantly dilated in response to the perception of social interaction, both from a second-person perspective (Experiment 1) and from a third-person perspective (Experiments 2 and 3). We thus confirmed for the first time that the innate preference for social interaction is directly reflected in the eyes. The findings fit well with the framework of social motivation theory, which proposes that we are driven by intrinsic social motivation to seek out pleasure in social interactions [4]. On the basis of this theory, social interaction stimuli should be able to gain attentional priority in visual processing. As evidence, interactive dyads are searched out more easily among non-facing dyads than the reverse [12], and are recognized more accurately in a backward masking task [13]. Therefore, it is probable that social interaction stimuli automatically capture attention and activate the arousal system, which in turn causes the pupil dilation effect. Concurrently, given the close relationship between reward processing and pupil size [2, 3], this dilation may also reflect the reward property of social interaction stimuli *per se*. Both accounts are compatible with the functions of the core neural substrate underlying the pupil dilation (i.e., the noradrenergic locus coeruleus, which is linked to arousal [1] and reward processing [14]).

Furthermore, we noted that the pupil dilation reached significance at an early stage of processing in Experiment 1 (from as early as 450 ms to 1300 ms) and at a relatively late stage in Experiments 2 and 3 (from $\sim$ 2000 ms to stimulus offset). One plausible explanation for this discrepancy is that observers, from a second-person perspective, can spontaneously extract the others' social intention towards themselves at the first glance, while it would take a relatively long time to decipher the mutual intention in a dyadic social interaction (from a third-person perspective) as they have to wait until the second agent makes appropriate responses. In this sense, the temporal characteristics of the pupil dilation likely mirror the dynamic processing of social interaction from different person views. On the other hand, the dynamic hierarchical processing of social interaction remains an intriguing question and should be suitably examined with the help of brain imaging techniques.

In sum, the present study remarkably substantiates that the perception of social interaction unfolds through pupil size, which sheds new light on the sensitivity of pupillometry to social motivation. It is worth noting that the ease of pupil recording may not only provide an applicable means of studying complex socio-affective processing in non-human animals, but also opens up a promising avenue for its application in the diagnosis of social cognitive disorders in human infants. Therefore, future studies are encouraged to investigate whether the pattern of the pupillary response to social interaction information offers a convenient biomarker to facilitate the early diagnosis of social cognitive disorders such as autism [15].

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Conflict of interest The authors have no conflicts of interest to declare.

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