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The relevance to social interaction modulates bistable biological-motion perception

Qiu Han [a,b], Ying Wang [b,c,d], Yi Jiang [b,c,d,e,*], Min Bao [a,b,c,*]

[a] CAS Key Laboratory of Behavioral Science, Institute of Psychology, Chinese Academy of Sciences, Beijing 100101, China
[b] Department of Psychology, University of Chinese Academy of Sciences, Beijing 100049, China
[c] State Key Laboratory of Brain and Cognitive Science, Institute of Psychology, Chinese Academy of Sciences, Beijing 100101, China
[d] CAS Center for Excellence in Brain Science and Intelligence Technology, Shanghai, China
[e] Chinese Institute for Brain Research, Beijing; Institute of Artificial Intelligence, Hefei Comprehensive National Science Center, Hefei, China

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A B S T R A C T

Social interaction, the process through which individuals act and react toward each other, is arguably the building block of society. As the very first step for successful social interaction, we need to derive the orientation and immediate social relevance of other people: a person facing toward us is much more likely to initiate communications than a person who is back to us. Reversely, however, it remains elusive whether the relevance to social interaction modulates how we perceive the other's orientation. Here, we adopted the bistable point-light walker (PLW) which is ambiguous in its in-depth orientation. Participants were asked to report the orientation (facing the viewer or facing away from the viewer) of the PLWs. Three factors that are task-irrelevant but critically pertinent to social interaction, the distance, the speed, and the size of the PLW, were systematically manipulated. The nearer a person is, the more likely it initiates interactions with us. The larger a person is, the larger influence it may exert. The faster a person is, the shorter time is left for us to respond. Results revealed that participants tended to perceive the PLW as facing them more frequently than facing away when the PLW was nearer, faster, or larger. These same factors produced different patterns of effects on a non-biological rotating cylinder. These findings demonstrate that the relevance to social interaction modulates the visual perception of biological motion and highlight that bistable biological motion perception not only reflects competitions of low-level features but is also strongly linked to high-level social cognition.

1. Introduction

For gregarious animals like humans, social interaction plays a vital role in our evolutionary history and daily life. Human beings cooperate and compete with each other to survive and thrive. Everyone in society communicates with others and reacts to their behaviors every day. Social interaction is so evolutionarily significant that the processing of socially relevant stimuli, including faces, body motion, etc., has been hardwired in the human brain (Allison, Puce, & McCarthy, 2000). Motion displays of two interacting persons bear faster detection in visual search, enhanced efficiency in working memory compared with two non-interacting persons (Ding, Gao, & Shen, 2017; Papeo, Goupil, & Soto-Faraco, 2019). Also, the interactive nature of a motion display is able to shorten its perceived time and reduce the perceived distance between interacting individuals (Liu, Yuan, Chen, Jiang, & Zhou, 2018; Vestner, Tipper, Hartley, Over, & Rueschemeyer, 2019). A communicative figure facilitates our sensitivity to detect another expected figure in noise (Manera, Becchio, Schouten, Bara, & Verfaillie, 2011). What's more, interactive actions are granted priority in access to conscious perception when competing with non-interacting actions (Su, Van Boxtel, & Lu, 2016). Arguably, social interaction has been an implicit force that profoundly shapes our perception of the world.

An essential component of social interaction involves rapidly retrieving other people's intentions based on different social cues. Biological motion, the motion pattern portraying the body movement of living creatures, conveys various social cues including actions, targets, and emotions (that can be extracted even from a long distance away) and thus enjoys superior processing in our visual system (Atkinson, Dittrich, Gemmell, & Young, 2004; Dittrich, 1993). We can readily retrieve the information conveyed by biological motion even when the

* Corresponding authors at: Department of Psychology, University of Chinese Academy of Sciences, Beijing 100049, China.
E-mail addresses: yijiang@psych.ac.cn (Y. Jiang), baom@psych.ac.cn (M. Bao).

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motion display is degraded as a sequence of dots depicting the human body's movement, which is referred to as the point-light walker (PLW, Johansson, 1973).

Among other cues, whether a person is facing us provides the first-line information regarding whether we need to get mobilized for an appropriate response, such as fast retreat or timely smile. The PLW has been extensively used to investigate the orientation perception for biological motion. This display is theoretically bistable when orthogonally projected; that is, it can be perceived as either facing the viewer (FTV) or facing away (FA) from the viewer. Intriguingly, this equivocal figure does not produce equiprobable outcomes. Research has established a common facing bias for the bistable PLW: The PLW would be perceived much more frequently as FTV than as FA for the vast majority of people (Vanrie, Dekeyser, & Verfaillie, 2004; Vanrie & Verfaillie, 2006). The origin of this perceptual asymmetry in bistable perception has remained debated.

In low-level explanations for facing bias, local properties of the body movement may drive perception in a bottom-up way. Specifically, the facing bias may be partially explained by a common convexity prior; that is, the visual system tends to construe a depth-ambiguous surface or curve as convex (Weech, McAdam, Kenny, & Troje, 2014; Weech & Troje, 2018). Accordingly, research has found that when the lower body was presented alone, a strong facing bias was observed, probably because the knees were perceived as convex; While for the upper body, an opposite bias was found, probably because the elbows were perceived as concave (Schouten, Troje, & Verfaillie, 2011). There is a possibility that people tend to base more on the lower part of the body to judge its orientation, leading them to adopt the FTV interpretation more frequently (Takahashi et al., 2011).

Although low-level factors have been shown to contribute, the role of high-level factors in the facing bias has also been investigated from different aspects. Some proposed the FTV figure is more threat-related since misinterpreting an approaching figure as receding is much more dangerous than otherwise. To avoid such danger, our perceptual system has developed a prior to preferentially choose the FTV interpretation (Vanrie et al., 2004). As an indirect proof, people showed larger facing bias for male PLWs than female ones, consistent with the common sense that males are generally deemed more threatening (Brooks et al., 2008). Yet, a follow-up study did not support a causal link between gender perception and the perceived facing orientation, while suggesting the facing bias was induced by information in the low part of the PLW figures (Schouten et al., 2011). Research has also established a connection between orientation perception and anxiety. Both stronger (Heenan & Troje, 2014, 2015) and weaker (Van de Cruys, Schouten, & Wagemans, 2013) facing biases have been found in the anxious group. The former could be explained by the threat-related attention in anxious individuals (Andrew & MacLeod, 1985; Pergamin-Hight, Naim, Bakermans-Kranenburg, van IJzendoorn, & Bar-Haim, 2015); the latter, however, is difficult to be accounted for by the threat explanation. More intriguingly, contradicted with the threat explanation where the facing bias is considered as arising from the basic motivation to avoid threats, another study regarded facing bias as a sign of willingness to approach another person. This study found guilty people showed more FTV percepts for the person they were guilty toward, and attributed the finding to the fact that guilty people manifest more prosocial behavior (Shen et al., 2018). While these findings indicate a role of high-level sociocognitive factors in FTV bias and its potential association with the perceived threat, threat alone seems insufficient to account for all the evidence.

For the ambiguous biological motion, the two interpretations differ in their relevance to social interaction: compared with a person facing away, a person facing toward us is more likely to initiate social interaction, would cause more severe consequences in social interaction, and claims our reaction more urgently. People's facing direction directly determined their relevance in terms of social interaction. Inversely, a figure's relevance to social interaction might also affect how we perceive its facing orientation. The processing of the ambiguous PLW may be biased by its relevance to social interaction: the more socially relevant FTV interpretation has gained preferential access to conscious perception, contributing to the facing bias.

To test this hypothesis, we systematically manipulated three factors closely pertinent to social interaction: the distance, the speed, and the size of the figure. If a socially relevant percept would gain priority in bistable perception, correspondingly, when a PLW figure is more relevant to social interaction, we would predict more facing percepts of that figure. The distance conveys the likelihood to initiate an interaction. Closer interpersonal distance denotes a higher probability of stimulation in nearly all modalities (Lloyd, 2009; Sorokowska et al., 2017). The size corresponds to the potential influence a person can exert. As for the speed, people with a fast walking speed require our response more urgently, enjoying higher priority in the perceptual processing system. These factors indeed successfully modulated the relevance to social interaction of the PLWs as confirmed by a rating session. These factors were all set to be task-irrelevant in order to examine their automatic influences on the perception of the PLW. Also, we had the PLW figure's configuration kept constant when manipulating each factor to equalize the influence of low-level features.

The experiments were conducted in a mimicked social scene to ensure the ecological validity of social interaction. Besides, to further probe whether the effects are specific to the social nature contained in biological motion, we included a rotating cylinder for comparison. The rotating cylinder, another typical bistable structure-from-motion stimulus, also elicits a perceptual bias: people generally see it as rotating toward them more frequently than away. Although the bases of this rotating-toward bias are not clear, they seem to differ from those of the facing bias: research has disclosed a role of genes in the perceptual bias for biological motion but not in that for a rotating sphere (Wang, Wang, Xu, Liu, & Jiang, 2014). Since both stimuli share most low-level processing including motion and structure-from-motion perception, their discrepancy is most probably due to the biological and social nature of the stimuli. By comparing the effects on these two stimuli, we could determine whether the results arise from a general structure-from-motion processing or is specific to biological motion.

2. Methods

2.1. Participants

A total of 38 subjects (age range = 18–28 years, age mean = 21.26 years, 21 females) participated in Experiment 1a, Experiment 2a, and Experiments 3a and 3b. Data from four subjects in Experiment 1a and Experiment 2a and five subjects in Experiment 3a were excluded from further analyses due to the ceiling effect in their performance (see 2.4. Analysis). 17 of the remaining subjects (age range = 18–24 years, age mean = 20.53 years, 12 females) also participated in Experiment 2c. 35 subjects participated in Experiment 1b and Experiment 2b (age range = 19–29 years, age mean = 23.7 years, 26 females). Data from one of them were excluded. The rating session enrolled an independent set of 26 subjects (age range = 19–29 years, age mean = 22.8 years, 17 females). All participants were with normal or corrected-to-normal vision and naïve to the purpose of the study. Written consents were acquired for their participation. Procedures of the experiments were approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences, with the work carried out in accordance with the Code of Ethics of the World Medical Association.

2.2. Apparatus

To increase the ecological plausibility of the scene that the figure is standing in front of the viewer, the stimuli were projected onto a blank wall in a dark room using a projector (Epson EMP-280, Epson Engineering Ltd., 60 Hz, 1280 × 768 pixels). The area covered by the projection subtended 328 cm horizontally and 200 cm vertically, with stimuli presented only on the right side of this area to avoid occlusion to the projector by the viewer. The participants stood facing this wall at a 260-cm distance from the wall, as illustrated in Fig. 1a. The shadow of the participants would not be projected on the display area. The procedure was achieved using custom programs based on Matlab (MathWorks Inc., MA, USA) with the Psychophysics Toolbox (Brainard, 1997). The perspective projection was implemented with the help of functions from the Biomotion Toolbox (van Boxtel & Lu, 2013).

2.3. Stimuli

PLW: The PLW we used in all the experiments was adapted from the same figure used in Schouten and Verfaillie (2010). The figure depicted a person walking on a black background at a speed of 1.43 s per step cycle (two steps, 84 frames with a playback speed of 60 frames per second). White dots were drawn only at the position of the head and main joints, including both sides of shoulders, elbows, wrists, hips, knees, and ankles, constituting a set of 13 dots in total. The initial frame in each trial of both the PLW and the cylinder was randomly chosen from the full sequence.

Cylinder: The cylinder consisted of 500 dots. Each dot possessed a rotating trajectory in 3D space which was then projected to a 2D plane (Vaina, Lemay, Bienfang, Choi, & Nakayama, 1990). On the 2D plane, half of the dots would move upwards and the other half downwards, constituting a transparent cylinder rotating pivoting on a horizontal axis. To the viewer, the cylinder would appear to be either rolling toward or away at any time, similar to a tire rolling on the ground. The width of the cylinder was kept equal to the width of the PLW's shoulder. The height and speed of the cylinder were determined based on the speed of the PLW so that the cylinder would roll over two steps' length of the PLW in a walking cycle. All the dots of the cylinder and the PLW (luminance, 32.9 cd/m^2) were drawn against a black background (luminance, 0.14 cd/m^2).

2.3.1. Distance manipulation in Experiment 1

When you look straight to the front, according to the central perspective principle, any point as high as your eye will be projected to the eye level at any hypothetic frontal-parallel screen. Assuming you are looking at a person of the same height as you, to reproduce what you see in a frontal-parallel screen, that person's eyes should be drawn at the same height of your eyes on the screen. This position is invariant regardless of the distance from you provided that that person is standing at the same ground level (illustrated in Fig. 1b and Video 1a). By setting the PLW's height as 170 cm, the PLW's eye position would be at 158 cm or so. In Experiment 1, the position of the PLW figure's eyes on the wall

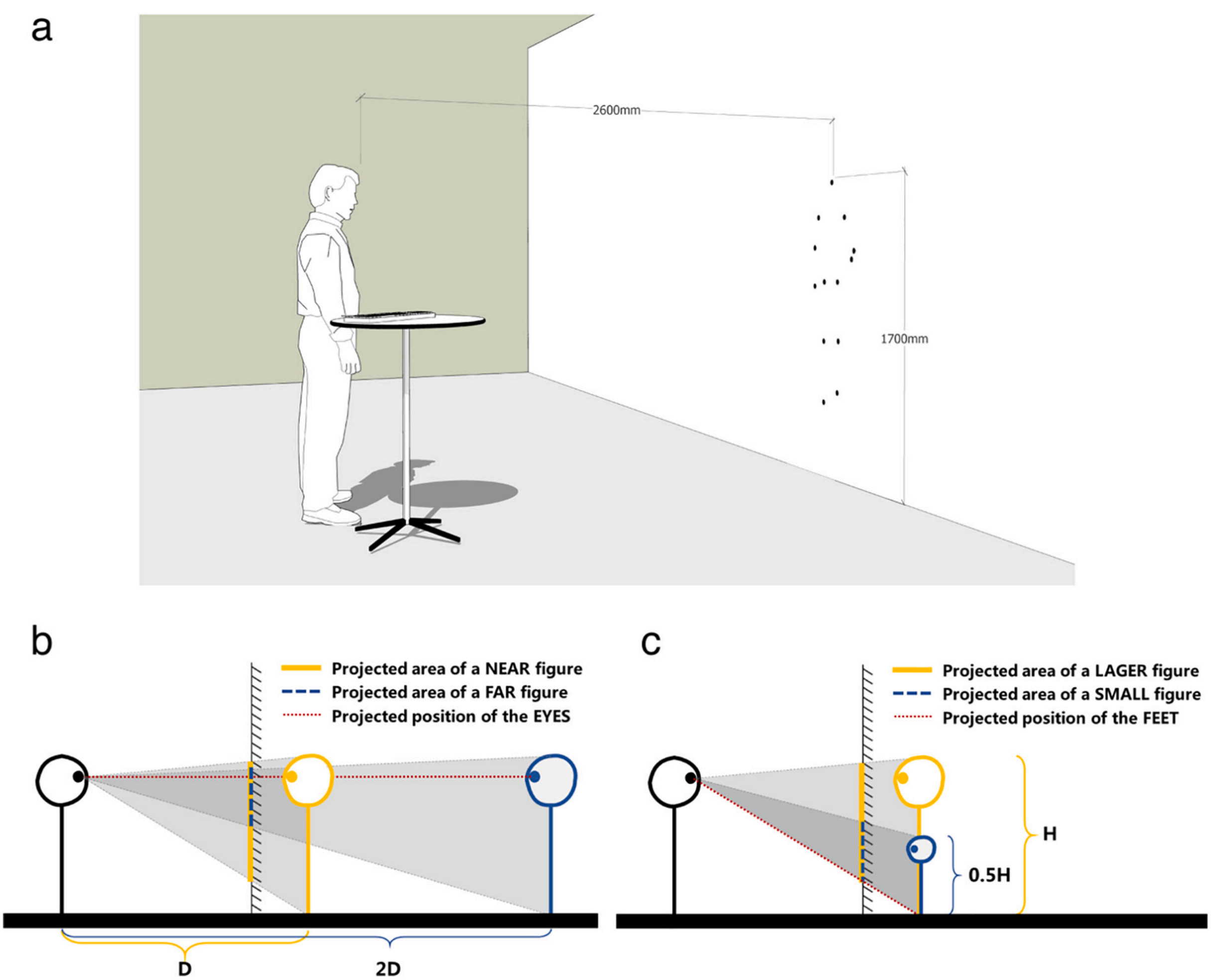

Fig. 1. Experiment Settings and Distance and Size manipulations. a: Experimental settings. The participant stood in front of a wall where the stimuli were presented at 260 cm and responded with a keyboard. b&c: Methods for distance manipulation and size manipulation. The vertical line with slashes represents a projection plane, i.e., the wall in the current experiments. Yellow and blue dashed lines abutting the wall indicate the projected areas on the wall of the hypothetical yellow and the blue person, respectively. In b, the eye position of the same person standing at different distances stayed the same after being projected. In c, the feet position of persons of different sizes but stand at the same place is fixed at one point on the wall. Note that the distances and heights in b and c are for illustration only and not in scale with parameters used in this study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

was fixed to 158 cm from the ground (here we set eye height at 158 cm for all subjects as an approximation, instead of individually adjusting for each subject according to their height. The difference between the two methods would be trivial). Now that the position of the PLW's eye on the wall had been found, because of foreshortening, the smaller the figure on the wall is, the further it will be perceived.

Here we used three levels of PLW size: 26.1° x 9.6°, 18.1° x 6.4°, 9.3° x 3.2° visual angle, corresponding to a perceived distance of 348 cm (near), 520 cm (medium), and 1040 cm (far). The size of the dots was also scaled in proportion to the size of the whole figure as a consequence of foreshortening, with a diameter of 0.69° visual angle in the near condition, 0.46° in the medium condition and 0.23° in the far condition. Consistently, the cylinder was set to be at the same height and width of a PLW in each condition. Each dot of the cylinder subtended 0.11029°, 0.057°, and 0.029° visual angles in the near, medium, and far conditions. The rotating speed was calculated from its perimeter so that the cylinder would move by the same distance as the PLW at the same time interval (Video 1b).

To provide a reference for a 3D space, a corridor consists of white dots was created as a background. These white dots were small in size (0.057° visual angle) and lined up together to constitute a sequence of white frames with a series of depth in 3D coordinate. The vanishing point of the corridor was also set at the eye position of the PLW on the wall so that the corridor and the PLW or cylinder are congruently in the same 3D space. The position of the PLW or cylinder was well matched to the real position where a person or cylinder should be when walking or rotating on the floor. Accordingly, they would be perceived to be touching the floor. Another important clue of depth, occlusion, was also introduced to establish the spatial relationship between the figure and the ground: outside every point of the PLW or the cylinder, a contour in the same color as the screen background was drawn to block the corridor. The width of the contour was 1.5 times the radius of the white dot for PLWs and ten times for cylinders in each condition, which was big enough to serve as an occlusion clue and not so big as to dwarf the inner white dots. With this contour, when the point of PLW and the corridor overlapped, the PLW would be unequivocally seen as in the foreground, blocking the corridor. The corridor's ground would serve as a reference frame for the position where the figure was standing. Besides, all the contours were beneath all the dots. No occlusion was caused between the dots on the front and the back of the cylinder. Thus, the contours cannot be used to disambiguate the cylinder's rotation direction.

2.3.2. Size manipulation in Experiment 2

If a person is standing at the same place, the projected position of his or her feet on the wall will stay the same regardless of his or her height (Fig. 1c, Video 2a). Thus, if the size of the PLW was scaled with its foot position fixed to a certain point on the screen, it would be perceived as persons of different sizes standing at the same distance. In Experiment 2, we used the same position as in the near condition of Experiment 1 and the same three size conditions, i.e., the largest figure in Experiment 1 corresponded to a normal-sized person standing at a near distance, and the medium and small figures were all unreasonably small persons standing at the same place. The size of the dots in large, medium, and small conditions was also scaled accordingly. The same manipulation was applied to the cylinders. The corridor was still drawn at the same position as a reference for the standing position. The black contour to separate figure and background were also retained (Video 2b).

2.3.3. Speed manipulation in Experiment 3

In Experiment 3, the figure size, dot size, and standing position of the PLW were kept consistent with those in the medium condition of Experiments 1 and 2. Unlike in other experiments where the size of the cylinder was matched with the PLW in each condition, in Experiment 3, the speed was strictly equalized for the cylinder and the PLW (Video 3a). Accordingly, the cylinder's perimeter was set to be the same as two steps' length, resulting in a visual angle of 4.6° x 6.4°. The position of the cylinder was centered at the hip position of the PLW. The original walking speed of 1.433 s/cycle was set as the medium walking speed of both the PLW and the cylinder. Fast (0.717 s/cycle) or slow (2.866 s/cycle) speed was achieved by skipping every other frame or doubling the duration of each frame. The same method was applied to the cylinder, generating cylinders rotating with angular velocities of 8.77, 4.38, and 2.19 rad/s for fast, medium, and slow conditions. The average drifting speed for each individual dot (moving from the upper to the lower side of the cylinder in half a cycle) was 18.2, 9.1, and 4.55°/s in three conditions, respectively (Video 3b).

2.4. Procedure

All subjects in the main experiments first completed a session to measure their points of subjective ambiguity (PSA) before the main experiments, after which they conducted orientation reporting task in Experiment 1a, Experiment 2a, and Experiments 3a and 3b, the order of which was counterbalanced across subjects. The intermediate rest time between experiments or sessions were at the participants' disposal. It took approximately 30 min for each subject to finish all the sessions. Experiment 2b was conducted on a different day. The recruited subjects were asked to finish the PSA measurement session again before conducting Experiment 2b in consideration of the variation of the PSA across days. These procedures took approximately 10 min. Experiments 1b, 2b were tested on a different group of participants and took about 10 min. An independent group of people rated the relevance to social interaction and the extent of the threat of the stimuli.

PSA measurement: Due to the potential ceiling effect caused by the high proportion of facing-the-viewer (FTV) percept in the majority of people and also the large interindividual variation revealed by previous literature and our preliminary experiment, the index of the proportion of FTV response was weak in statistical power. To solve this problem, we adopted perspective projection instead of orthogonal projection to render PLWs as seen from the front or back. Compared to orthogonal projection, objects "distort" when viewed with perspective in real life. A cube's front face would have a larger retinal size than the back although they are identical. By presenting a set of dots with calculated "distortion" which conforms to visual experience for viewing a person from the back, the PLW would look more like seen from the back rather than otherwise. Thus, we could strengthen the impression of viewing from a certain side by increasing the degree of perspective (see Schouten & Verfaillie, 2010 for details). This way, we were able to counter each viewers' bias and adjust their FTV percentages to around 50%.

To get the degree of perspective at which they equiprobably perceived the PLW figure to be facing toward or away, subjects were first instructed to conduct a point of subjective ambiguity (PSA) measurement session. In this PSA measurement session, the PLW figure was at a distance equivalent to the medium distance of Experiment 1, of a size equivalent to the medium size of Experiment 2 and at a speed equivalent to the medium speed of Experiment 3, varied only in its degree of perspective from trial to trial. The degree of perspective in each trial was determined by two interleaved one-up one-down staircases; each consists of 40 trials. After a beep, the figure was presented on the screen for a full cycle (1.433 s), and then a blank screen was shown. Subjects indicated their perception by a keypress, with the Up-Arrow key for facing away and Down-Arrow key for facing toward the subject. A successful keypress would be accompanied by another beep. A white noise texture was shown for 0.5 to 1 s as a measure to obviate potential carry-over effect, i.e., subjects' perception in one trial might permeate the subsequent trials. Then the next trial began. The PSA was calculated by averaging the degree of perspective of the last 4 reversals of both staircases. The averaged degree of perspective was applied to all the PLW stimuli in the rest sessions.

It is noteworthy that a rotating-toward-the-viewer (RTV) bias for an orthogonally projected cylinder was found in previous literature and also confirmed in our preliminary test using an orthogonally projected cylinder. In this situation, the cylinder was also presented in perspective. The degree of perspective was kept the same in all subjects rather than determined individually for the experiment's succinctness. Therefore, the average proportion of 'perceived as approaching' responses for the cylinder may differ from that of the PLW.

Experiment 1: Experiment 1a tested the effect of distance on the PLW stimuli. Experiment 1b tested the same factor but on the cylinders. During these sessions, the corridor made from white dots was presented on the screen throughout the experiment. With a beep as an alarm, a PLW figure (Experiment 1a) or a rotating cylinder (Experiment 1b) at different distances appeared overlaying on the corridor. The stimuli were shown on the screen for 1.433 s and then disappeared. The subjects were instructed to respond as soon as possible, with no need to wait for the figure to disappear. We explicitly clarified in the instruction that it was the direction that the figure was orienting that they should judge, to avoid that subjects might choose the direction that the figure was shifting to, which is opposite to the facing direction when they perceive the person as walking backward (Vanrie et al., 2004). After the response was given, there would be another short beep and then a white noise texture shown on the screen for 0.5 to 1 s. Both Experiments 1a and 1b consisted of 120 trials, 40 trials for each condition. The order for different conditions was randomized within each experiment.

Experiment 2: the procedures of Experiments 2a (the PLW) and 2b (the cylinder) were identical to those of Experiment 1a and 1b. Experiment 2c was a further confirmation of Experiment 2a. One possibility exists that the size of the relatively abstract dot-made corridor in Experiment 2a was vulnerable to other explanations. Size has been found to affect the perceived distance when the intrinsic assumption of the objects' physical size played a role to maintain the size constancy (Hastorf, 1950). Due to the high homogeneity of an adult's size, instead of using the abstract corridor as a reference to infer the size of the PLW, our perceptual system may be prone to maintain a constant percept for the human figure and change the perceived size of the corridor accordingly. The effect of size would be thereby confounded by the effect of distance. To help sustain a percept that the figures were indeed scaled to smaller rather than just further away, a solid clue of a fixed-size space was essential.

To this end, photographs of real corridors or hallways placed with human-scale furniture were used. The vanishing point of each picture was set at the eye position of the PLW figure as for the dot-array-version corridor. To avoid certain effects caused by the low-level features of one particular picture or the emotion it evoked, five different pictures of delightful surroundings and five of scary surroundings were chosen. Subjects first completed an evaluation session in which the degree of delightfulness or horror of the pictures was indicated by clicking on a scale bar. The picture with the highest score of delightfulness and the one with the highest score of horror was used as the background in the subsequent facing direction judgment session. Based on the mean luminance of the picture, the dots were rendered either white (on dark pictures) or black (on bright pictures) and were circled with an edge of the opposite color to increase their visibility against the background picture. Another important depth cue, the shadow, was also introduced here to establish the credibility of the relationship between PLW and the surroundings: an elliptical grey blob, whose size was scaled proportionally to the PLW, was draw on the picture at the position the figure standing at to mimic a shadow of the figure. This cue effectively contributed to fixing the PLW's position in depth (Video 2c). The procedures were identical to those of Experiment 2a except that the background would be first presented for 0.5 to 1 s before the PLW appeared to avoid distraction by the onset of the pictures.

Experiment 3: In this experiment, the effect of speed on both the PLW figure and the cylinder was tested. To further reduce the potential carry-over effect, the two types of stimuli were randomly interleaved. The total trial number was 240. Trials of different speeds were also randomized. For all conditions, the stimuli were presented for a full cycle if no response was made: two steps for PLW figure, 360° rotation for the rotating cylinder, resulting in a duration of 0.717, 1.433, and 2.866 s for fast, medium, and slow conditions, respectively. The presentation and response procedure were the same as in Experiment 1, except that the corridor was removed.

Rating session: We implemented a subjective rating session to ensure that the factors we adopted indeed modulated the stimuli's relevance to social interaction. Also, to test the possibility that threatening information might contribute to the results, we also gathered ratings on perceived threat. This session used the same stimuli and was conducted in the same settings as that of the other experiments. Firstly, a PLW or a cylinder of different distances, sizes, or speeds was presented. After that, two descriptions were shown on the screen in sequence. First: You feel that the figure is likely to have social interaction with you or exert social influence on you, requiring your social response. Second: You feel the figure might threaten you. A horizontal scale bar was posited below the description. The left end of the scale bar was labeled as "1: not at all" and the right end as "100: very strongly". The subjects were instructed to click on a position of the scale bar according to the extent by which their feelings evoked by the figure agree with the description. After that, the subjects pressed one of two keys to indicate whether the figure they saw was facing/rotating toward or away from them. Only scores for a forward-facing/rotating figure was recorded as the rating results for this stimulus. This procedure was repeated for all the conditions used in the FTV measurement experiments, i.e., 3 levels for 2 stimuli in 3 experiments, the order of them randomized among participants.

Analysis: Trials with a reaction time shorter than 200 ms ($\leq$0.12% for all experiments) were deemed as invalid trials and discarded from data analysis. The proportions of trials in which an FTV response was made were calculated and compared among conditions. A ceiling effect was deemed to happen when the proportion of either FTV or FA percept exceeded 90% in all three conditions. Data from subjects showing a ceiling effect even after the perspective method was applied were excluded from further analysis. For statistical comparison between stimulus types, subjects would be removed from the analysis of Experiment 3 if a ceiling effect for either of the PLW and cylinder stimuli was found. The FTV/RTV proportions in each experiment were subjected to a one-way ANOVA and Tukey's Multi-comparison method, and results of different stimuli were compared using a two-way repeated measurement ANOVA. In all the ANOVA tests where a Mauchly's test indicated a violation of the assumption of sphericity ($p < .05$), degrees of freedom were corrected with Greenhouse-Geisser estimates of sphericity. The link to raw data was provided in Supplementary material.

3. Results

3.1. Experiment 1

As shown in Fig. 2a, the proportion of FTV percept was significantly affected by the perceived distance for the PLW ($F(1.30, 42.9) = 17.56$, $p < .001$, $\eta_p^2 = 0.35$). Multi-comparison showed that the FTV proportion differed among all the three conditions ($ps \leq 0.01$). For the cylinder, however, despite the significant main effect on the RTV proportion ($F(1.19, 39.4) = 8.37$, $p < .004$, $\eta_p^2 = 0.20$), only the far condition showed difference from both the other conditions ($p \leq 0.007$). By contrast, the near and medium distance produced comparable results ($p = .78$). A two-way ANOVA with stimuli type as a between-subject factor and distance as a within-subject factor showed a non-significant interaction between these factors ($F(1.29, 85.4) = 1.17$, $p = .30$, $\eta_p^2 = 0.017$).

3.2. Experiment 2

For the PLW, in both Experiments 2a and 2c where dot arrays and real-world scenes served as the background respectively, the FTV percept proportion was considerably larger when the size was larger

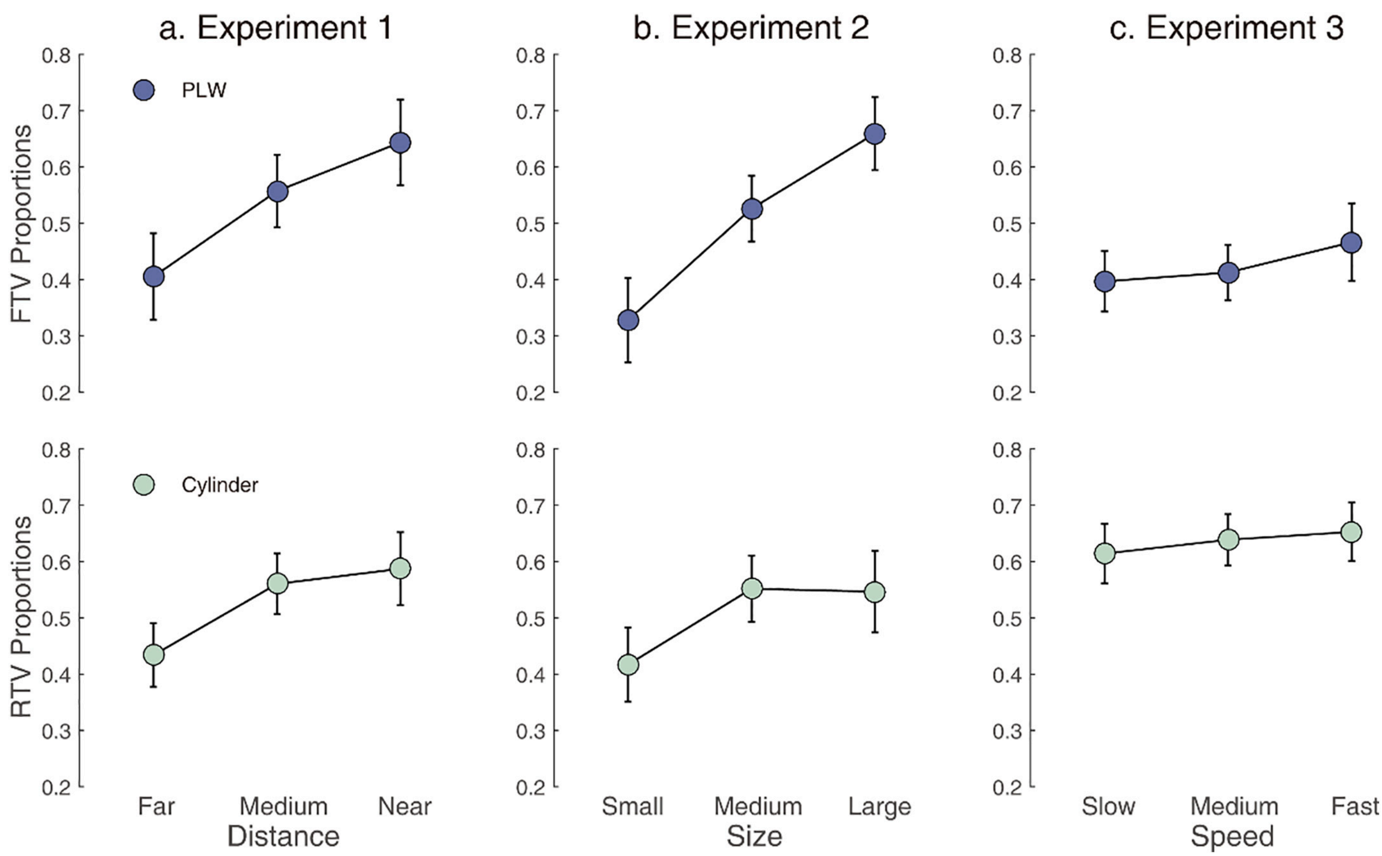

Fig. 2. The Proportions of FTV/RTV Responses. Error bars indicate 95% confidence intervals.

(Experiment 2a: $F(1.37,\ 45.1) = 45.53$, $p < .001$, $\eta_p^2 = 0.58$, Fig. 2b; Experiment 2c: $F(1.55,\ 24.80) = 22.74$, $p < .001$, $\eta_p^2 = 0.59$, Fig. S1). Multi-comparison indicated significant differences between all the three pairs of size levels in both experiments ($ps \leq 0.025$). Further, we tested if the size effect differed when different backgrounds served as the depth cues. The data of the subjects who participated in both Experiment 2a and 2c (17 subjects) were entered into a two-way ANOVA with background type and stimuli size as the within-subject factors. No significant main effect of background type was found ($F(1,\ 16) = 2.97$, $p = .10$, $\eta_p^2 = 0.16$), and the interaction between background type and size was not significant either ($F(1.42,\ 32) = 1.08$, $p = .34$, $\eta_p^2 = 0.063$, Fig. S1). The correlation of each subjects' performance between the two experiments was strong (according to Cohen's convention; $r = 0.687$, $p < .001$). These results suggested that the dot array background served as a successful hint of 3D space as pictures of the real-world scenes.

For the cylinder, the effect of the size was also significant ($F(1.41,\ 46.5) = 6.2$, $p = .009$, $\eta_p^2 = 0.158$). Different from that for the PLW, the effect of small condition was significantly smaller than that of medium and large conditions ($p \leq 0.011$). Effects of large and medium conditions, however, were quite similar with each other ($p = .99$). Critically, there was a significant interaction between stimuli type and size ($F(1.4,\ 92.1) = 6.88$, $p = .005$, $\eta_p^2 = 0.094$), confirming that the factor of size generated different patterns of influence on the PLW and the cylinder.

It is possible that despite the difference in experimental settings, the effects of distance and size could be attributed to the same factor, considering that stimuli of the near, medium, and far conditions shared the same retinal size as in the large, medium, and small conditions. To address this issue, we compared whether the retinal size produced different results when set as a distance cue from when set as a size cue. If entirely overlapped mechanisms underlie the size and distance factors, behavioral outcomes led by the two factors should resemble each other in any aspect (including the aspect either related or unrelated to the FTV index). We found a non-significant trend of interaction between retinal size and experimental setting (distance and size) on FTV proportions ($F(1.61,\ 53.1) = 2.57$, $p = .097$, $\eta_p^2 = 0.072$). However, there was a significant interaction of reaction time between these two factors ($F(1.78,\ 58.8) = 4.10$, $p = .026$, $\eta_p^2 = 0.11$, see Fig. 3). In other words, the distance manipulation and the size manipulation produced different patterns in

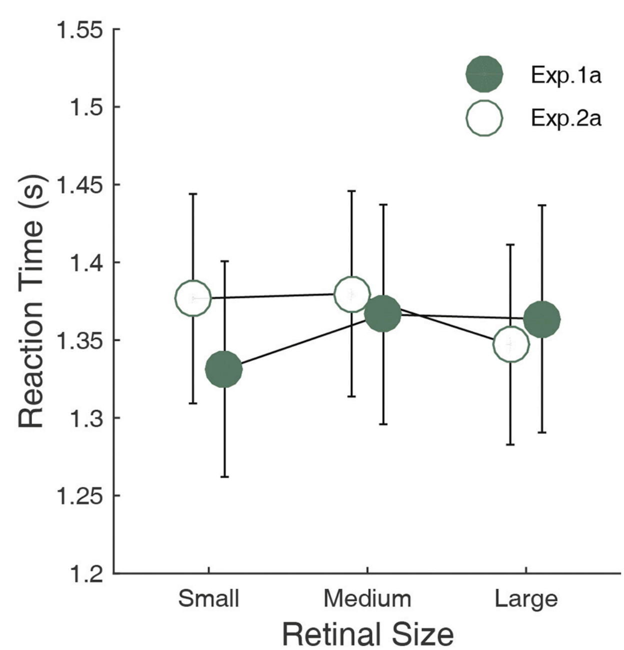

Fig. 3. Reaction times of the PLW in distance and size experiments as a function of retinal size. Error bars indicate standard errors.

reaction time, despite their similar influence on the FTV perception. Such discrepancy thereby suggests that the mechanisms underlying these two factors were not identical. Retinal size might have contributed to the results, but the perceived distance and the perceived size may also play a part.

3.3. Experiment 3

The FTV proportions of experiment 3 were plotted in Fig. 2c. Speed showed a marginally significant ($0.05 \le p < .1$) effect on the FTV proportion for PLW ($F(1.4, 44.9) = 3.38$, $p = .059$, $\eta_p^2 = 0.096$), i.e., the PLW was more likely to be perceived as FTV when the speed was faster. However, the same trend was not shown on the RTV proportion for cylinder ($F(1.50, 48.2) = 1.34$, $p = .27$, $\eta_p^2 = 0.04$). No pair-wise comparison survived Bonferroni correction.

Because of the different experimental settings of perspective cues for the PLW and the cylinder (see Procedure), the mean FTV proportions for two types of stimuli may differ even without the manipulation of their speed, as was shown in Experiment 3 when their sizes were not matched. To eliminate this difference when comparing the results of these two stimuli, we first z-transformed the data before conducting the two-way ANOVA. According to the two-way ANOVA with stimuli type and speed as within-subject factors, the main effect of speed was significant ($F(1.64, 52.4) = 4.60$, $p = .014$, $\eta_p^2 = 0.13$), without an interaction between stimuli type and motion speed ($F(1.41, 45.0) = 0.44$, $p = .58$, $\eta_p^2 = 0.013$).

3.4. Rating

As illustrated in Fig. 4, both the PLW and the cylinder elicited more threatening feelings when they are nearer, larger, or faster (one-way ANOVA, $Fs \ge 8.94$, $ps \le 0.002$, $\eta_p^2 s \ge 0.26$). While only the PLW showed higher relevance to social interaction (PLW: $Fs \ge 5.83$, $ps \le 0.008$, $\eta_p^2 s \ge 0.19$; cylinder: $ps \ge 0.29$). Further two-way ANOVA with experimental manipulation and rating dimension as factors showed a main effect of dimensions: regarding the PLW, the ratings for social relevance was higher than for threat ($Fs \ge 10.7$, $ps \le 0.003$, $\eta_p^2 s \ge 0.30$) and the contrary was true for the cylinder ($Fs \ge 32.5$, $ps \le 0.001$, $\eta_p^2 s \ge 0.56$). When comparing the ratings for different stimuli on the same dimension, on social interaction, we found an interaction of experimental manipulation and stimulus type for all the three factors ($Fs \ge 5.66$, $ps \le 0.006$, $\eta_p^2 s \ge 0.19$). Only the PLW was evaluated as more relevant to social interaction when it was nearer, larger, or faster (Fig. 4, upper row). On threat, the three factors induced comparable evaluation for the PLW and the cylinder (Fig. 4, lower row, main effect of stimuli type: $Fs \le 4.14$, $ps \ge 0.053$, $\eta_p^2 s \le 0.14$). To conclude, for the PLW, for the larger, nearer, or faster stimuli successfully elicited stronger feelings of relevance to social interaction and also the feelings of being threatened, with the former overall stronger than the latter. For the cylinder, only threat was perceived.

4. Discussion

Within a verisimilar social context, the current study tested the effect of three factors critically pertinent to social interaction on how we perceive the orientation of a bistable PLW stimulus. The data revealed a pattern that the more relevant the ambiguous human figure was to social interaction, the more likely it was perceived as FTV. This pattern is consistent across different socially relevant factors. As evidenced by the rating scores, the three factors indeed significantly modulated the observer's evaluation of the PLW regarding its relevance to social interaction. In contrast, for non-biological motion as represented by a rotating cylinder, the same manipulations did not affect the subjective evaluations in aspects of social interaction. Moreover, the modulation of the RTV percept was present only for the distance and the size but not for the speed experiment. Particularly, in the size experiment, the size effect showed significantly different patterns on the PLW and the cylinder. Considering the matched low-level processing of the PLW and the cylinder among conditions and their difference in rating scores, the dissociation of the FTV and RTV proportions most likely results from the

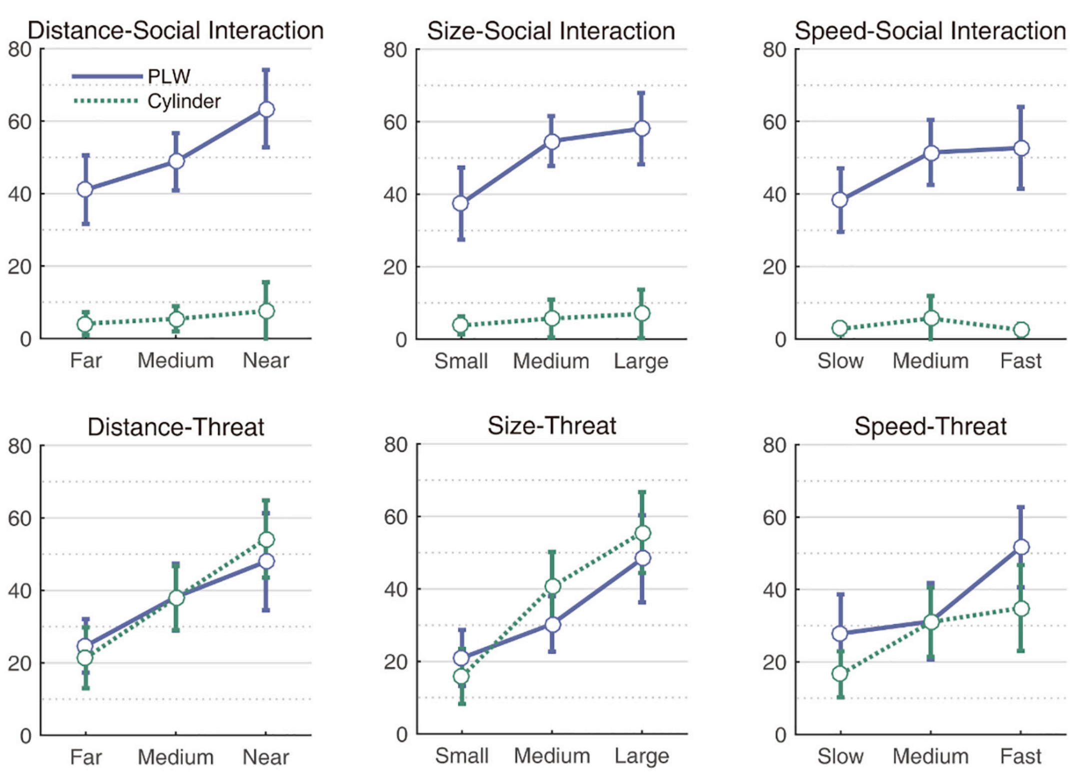

Fig. 4. Rating Results for Stimuli Used in Three Experiments. Upper row: scores on the relevance to social interaction; Lower row: scores on threat. Error bars indicate 95% confidence intervals.

social or biological nature contained in the PLW.

Despite their difference in social interaction ratings, the PLW and the cylinder elicited a comparable extent of threat feelings, as indicated by the rating scores. However, it remains possible that the threat elicited by these two stimuli do not have the same origin. Social interaction includes both benefits and threats. This means, on the one hand, that an intersection between social interaction and threat exists (Green & Phillips, 2004; Roelofs, Hagenaars, & Stins, 2010). Indeed, the ratings for relevance to social interaction and threat were highly correlated for PLWs ($rs \geq 0.52, ps \leq 0.001$) but not for cylinders ($ps \geq 0.63$), suggesting that the perceived threat may arise partially from the relevance to social interaction, specifically for the PLW. On the other hand, social interaction and threat have non-overlapping conceptual parts: benefits from social interaction and non-social threat (e.g. threat brought by a cylinder is from the danger to collide). From this standpoint, social interaction and threat are not simply taken as an identical concept, while it does not necessarily mean that they could not work in tandem to influence the FTV percepts. A comparable extent of threat might explain the changes from the small to medium condition, resulting in comparable FTV/RTV proportions. Although the threat ratings continued to rise from medium to high, the increase failed to influence the perception of the cylinder probably because the effect of the threat has reached its asymptote. This may explain the relatively weak dissociation between the PLW and the cylinder on FTV/RTV performance in Experiments 1 and 3. The specific role of social interaction still requires further research to be established more firmly and to be understood in more detail. Nevertheless, the significant interaction in Experiment 2 rules out a general threat explanation for both stimuli. These findings extend the current threat explanation about the facing bias of the PLW to the more general account of social relevance.

According to the error management theory, our decision-making process is biased by its consequences. When confronting ambiguous situations, two types of error may occur, falsely missing or falsely alarming a signal. A humanly engineered system would be biased toward the error which is less costly (Haselton & Buss, 2000). In human society, to gain the benefit of social interaction or to avoid possible harm caused by other people, one needs to make timely responses to social scenes, whether approach or avoidance. It is thus more costly if you falsely regard a person who is actually facing you as facing away than otherwise, which could have contributed to the evolution of facing bias. This explanation suggests the visual perception is not only a reflection of the stimulus configuration *per se*. When the stimulus is associated with our surviving or thriving, its processing is critically linked to its biological or social meaning. As shown in the current study, the same figure would be processed differently when attached with different significance in social scenes.

Distance is an important cue signaling the interpersonal relationship in social space (Sorokowska et al., 2017). Decreasing the distance from a person would concomitantly increase the possibility to initiate an interaction with that person. People far away may be irrelevant to you; When they are within sight, they could greet you by waving; When they are within reach, a talk or a fight is possible. A certain distance range will be inherently delineated as safe or comfortable for social interaction, while a too close interpersonal distance would cause arousal (Epstein & Karlin, 1975). Previous research has suggested that social interaction would compress the perceived distance between interacting entities, especially when the interaction is of high quality (Shao, Yin, Ji, Yang, & Song, 2020; Vestner et al., 2019). Reversely, in the current study, we demonstrate a modulation effect of the distance between others and us on how we perceive others' facing direction.

As shown in Experiment 2, the reduction in the size of the figure remarkably lowered the extent of facing bias. The size is positively associated with people's ratings about a person's strength and even leadership ability (Lindqvist, 2012). In this sense, the larger the person is, the more considerable social influence it is capable of exerting on others in society. Also, when the size of a PLW figure was rendered unreasonably small, it would be less an authentic human being but more a virtual figure as if seen on a TV screen and thereby less likely treated as a communicative target by the viewer. Both explanations demonstrate the role of the figure's relevance to social interaction. In previous studies, size has been shown to influence various perception processes, including emotion discrimination and modulation. Size reduction of an affective picture lowers the modulation effect of its emotion valence on event-related potentials in the early stages (De Cesarei & Codispoti, 2006). Larger stimuli also evoke higher arousal embodied in higher skin conductance (Reeves, Lang, Kim, & Tatar, 1999). It is worth noting that these effects were mostly explained by the associated distance change: the same object will be perceptually postulated to be nearer when presented in large sizes. In the current work, by fixing the perceived distance, the function of the perceived size *per se* was revealed.

Faster speed indicates faster contact, therefore, more opportunities to interact, less time for the viewer to react timely and properly. In previous studies, looming sounds were shown to be perceived as faster than receding ones, indicating the likelihood of colliding warps time perception (Neuhoff, 2016). Here we demonstrated that the potential of social interaction affects bistable visual perception. However, in the current study, the effect of speed on PLWs was not obvious. Nevertheless, the different patterns of reaction time between the PLW and the cylinder may indicate a social factor mediating the response for the PLW.

Because of its biological and social significance, the neural basis for biological motion processing has been extensively investigated. Among other cerebral areas, the superior temporal sulcus (STS) has been repetitively confirmed to be a hub for processing of social stimuli such as human body, face, gaze direction et al. (Allison et al., 2000; Blake & Shiffrar, 2007; Sokolov et al., 2018). A subcortical area, the amygdala, is also involved in social processing, with a reciprocal connection with STS (Adolphs, 1999; Allison et al., 2000). For example, the amygdala allocates processing resources for ambiguous and biologically salient stimuli: the positive and the negative interpretation of an ambiguous face corresponding to different patterns of amygdala activation (Kim et al., 2004; Kim, Somerville, Johnstone, Alexander, & Whalen, 2003). On the other hand, the amygdala is in charge of threat perception for both animate (Adolphs, 2008; De Gelder et al., 2014) and non-animate (Coker-Appiah et al., 2013) threatening stimuli. Combined with the current data, we speculate that the modulation of the three factors on the perceptual content of bistable biological motion may not depend on anatomically earlier visual cortex such as MT but involves the processing of STS. Besides, it's possible that STS also receives feedback projections from the amygdala during this process (Oram & Richmond, 1999). We may make some assumptions about the mechanism: the PLW, when presented nearer, larger or faster, may be labeled as more socially salient by the amygdala. After receiving feedback signals from the amygdala, the STS's activation for a more socially relevant figure is enhanced, leading to more FTV percepts. By contrast, the perception of the cylinder may involve activity of the amygdala but not that of the STS. Still, the current behavioral method does not allow us to probe into the specific neural mechanism underlying. A recent study employing EEG frequency tagging showed that the processing of the biological nature of point-light dancers occurred at an intermediate level of the cortical hierarchy, while the processing of the social interactions occurred at a higher level (Alp, Nikolaev, Wagemans, & Kogo, 2017). Tools like electroencephalography, neuroimaging, and neuromodulation are informative to provide more elaborate evidence.

In summary, the current work provides evidence that the distance, size, and speed of a bistable biological motion stimulus remarkably influence which interpretation comes into consciousness. The current data suggest that threat is probably not the only cognitive factor contributing to facing bias and point to the potential role of the stimuli's relevance to social interaction. Our findings suggest a role for top-down processing in the bistable perception of both biological and non-biological motion besides bottom-up processing, providing a more comprehensive explanation for high-level factors of facing bias. Further, the results also illustrate the effect of the social nature of a bistable stimulus on its visual processing, which is worth further investigation in future studies.

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Declaration of competing interest

The authors declare no competing interests.

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